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MODERN PIANO TUNING
AND
ALLIED ARTS

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BY
WILLIAM BRAID WHITE

Author of
Piano Playing Mechanisms
The Acoustic Design and Construction of
the Piano, Etc.

2nd Edition—Revised

WITH DRAWINGS, DIAGRAMS,
TABLES, NOTES AND AN INDEX

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PREFATORY NOTE

TO THE SECOND EDITION

The first edition of this book was published in the year 1917. In due course it has found its way into all parts of the English-speaking world, and a second edition has now become necessary.

In preparing this I have not thought it necessary to make any important changes in the general plan or in the text of the book. It should, however, be noted that the adoption in 1925 by the Music Industries Chamber of Commerce in the U. S. A. of the 440 pitch has involved the re-calculation of the tables of frequencies, beat-rates and so on, although the differences are in reality very slight. The text has been carefully read, where necessary corrected, and in some cases brought up to date. Otherwise the book in general remains what it was when it was first published.

A complete and rather detailed treatise on the acoustic design and construction of the piano is to follow, within a short time, through the press, this second edition of Modern Piano Tuning. I venture to think that it will form a companion and complementary work to this one, covering, with it and

with my "Piano Playing Mechanisms" (1925), the whole field of piano technology.

I renew my thanks to my brother, Mr. H. Sidney White, M. E., for the drawings which he furnished for this book.

WILLIAM BRAID WHITE.

New York, 1929.

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Chapter I

MECHANICS OF THE MUSICAL SCALE

He who undertakes to master the art of piano tuning should have some acquaintance, exact rather than comprehensive, with that general body of knowledge known as acoustics, or the science of sound. Piano tuning itself, as an art, is merely one of the branches of practical acoustics; but in order that the branch may be understood it is first necessary to understand the trunk, and even the root.

No one, however, need be frightened by the above paragraph. I am not proposing to make any excursions into realms of thought too rarefied for the capacity of any man who is likely to read this book. Every page which follows will be found to be perfectly practical and intelligible. Some discussion of the ascertained facts about the production and composition of sound in general, and of musical sound in particular, is, nevertheless, indispensable.

What is Sound? When a street-car runs over a crossing where another line intersects, we usually hear a series of grinding crashes, which we attribute perhaps to flat tires on the wheels or to uneven

laying of the intersecting trackage. The most prominent feature of such a series of noises is their peculiarly grating and peculiarly spasmodic character. They are on the one hand discontinuous, choppy and fragmentary, and on the other hand, grating, unpleasant to the hearing, and totally lacking in any but an irritant effect. These are the sort of sounds we speak of as "noise." In fact, lack of continuity, grating effect and general fragmentariness are the distinguishing features of "noises," as distinguished from other sounds.

If now we listen to an orchestra tuning up roughly off-stage, the extraordinary medley of sounds which results may, and frequently does, have the effect of one great noise; although we know that each of the single sounds in the uproar is, by itself, musical. So it appears that noises may be the result of the chance mixture of many sounds not in themselves noises, but which may happen to be thrown together without system or order. Lack of order, in fact, marks the great distinction between noises and other sounds.

If again we listen to the deep tone of a steamer's siren, or of a locomotive's whistle, we are conscious of a different kind of sound. Here is the immediate impression of something definite and continuous, something that has a form and shape of its own, as it were, and that holds the same form so long as its manifestation persists. In fact, we

shall find that what are called musical sounds are simply more perfect examples of the continuity, the order and the definite character which we noticed in the locomotive whistle's sound. The more highly perfected the musical instrument, the more perfectly will the sounds evoked by it possess the qualities of continuity, order and definite form.

Continuity, persistence and definiteness, then, are the features which distinguish musical sounds from noises. There are, therefore, only two kinds of sounds—musical sounds and noises.

Now, what is sound? The one way in which we can know it, plainly, is by becoming conscious of what we call the sensation of sound; that is, by hearing it. If one considers the matter it becomes plain that without the ability to hear there would be no sound in the world. Sound cannot exist except in so far as there previously exist capacities for hearing it. The conditions that produce sound are obviously possible, as we shall soon see, to an interminable extent in all directions; yet what we may call the range of audible sound is very small indeed. We can hear so very little of the conceivably hearable material; if I may use so rough an expression.

So it becomes quite plain that sound cannot be considered as something in itself, existing in the sounding body apart from us, but must rather be

thought of as the *form* in which we perceive something; the form, in fact, in which we perceive the behavior of certain bodies, which behavior could not be perceived in any other way. Sound then can be considered only from the viewpoint of the physical laws which govern the behavior of the bodies in question. The laws which govern that sort of behavior which we perceive as sound, alone form the subject of acoustics. Why we should experience these perceptions as sound rather than as light or heat is not a question to be decided by acoustics; is not a problem of the natural sciences, but of metaphysics.

Limited therefore to a strictly mechanical investigation, let us consider the production of sound from this viewpoint. Suppose that I strike a tuning-fork against the knee and hold it to the ear. I am conscious of a sound only moderate in intensity but of persistent and quite definite character, agreeable, and what we call "musical." No one has any hesitation in calling this a "musical sound." But what produces it, physically speaking? It can be discovered by making a simple experiment.

By lightly touching the prongs of the fork while it is sounding I discover them to be in a state of vibration. If I examine them under a microscope I shall perhaps be able to detect an exceedingly rapid motion. In order, however, to make sure of

the existence of these unseen vibrations, it is only necessary to obtain a sheet of glass and smoke one surface of it by passing it over the flame of a candle. Then let a tuning fork be fitted with a very light needlepoint stuck on the end of one prong with a bit of wax, in such a position that if the sheet of glass be placed parallel with the length

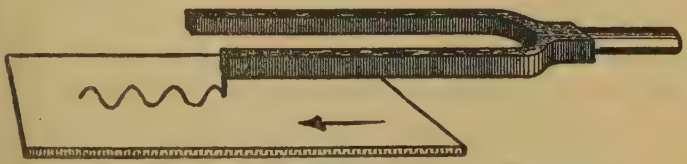

FIGURE 1

of the fork, the needle point will be at right angles to both.

Now set the fork to sounding, and hold it so that the needle point lightly touches the smoked surface. Have a second person then move the sheet of glass lengthwise while the fork is held still. At once the needle point will trace out a continuous wavy line, each wave being of that peculiar symmetrical form known technically as a curve of sines or sinusoidal curve. By adjusting the experimental apparatus with sufficient exactness, we may find out how many of these little waves are being traced out in any given time. Each of these waves corresponds to one vibration or pendulum-like back and forth motion of the fork. By exam-

ining the wavy line with close attention, we shall see that if the motion of the glass sheet has been uniform, each sinusoid is identical in size with all the others, which indicates that the vibrations are periodic, that is to say, recur at regular intervals, and are of similar width or amplitude.

We may therefore conclude from this one experiment that the physical producer of musical sound is the excitation of the sounding body into periodic vibrations.

Suppose again that one listens to the noise of the machinery in a saw mill. When the circular saw starts to bite at a piece of wood one hears a series of grating cracks, which almost instantly assume the character of a musical sound, rough but quite definite. As the saw bites deeper into the wood the sound becomes, first lower, then higher, until it mounts into a regular song. As the saw comes out through the wood, the sounds attain momentarily to a high pitch and then instantly die away. What is the cause of this phenomenon?

The circular saw is a steel wheel with a large number of teeth cut in its circumference. Suppose there are fifty such teeth. At each revolution of the wheel, then, each tooth will bite the wood once. If the wheel revolves at the rate of say four revolutions per second, it follows that there will be four times fifty or two hundred bites at the wood in this time. That means that the wood will re-

ceive two hundred separate scrapes per second. Hence, the rotation of the wheel will be slightly interrupted that number of times in one second. Hence, again, the surface of the air around the wheel will be vibrated back and forth just as many times, because the entry and emergence of each tooth will cause an alternate compression and suction on the air around it. Again, suppose we stand five boys up in a row, one behind the other, so that each boy has his outstretched hands upon the shoulders of the boy in front of him. Push the last boy. He falls forward, pushes the next and regains his position. The next boy falls forward, pushes the third boy and regains his position. Third falls forward, pushes fourth and regains his position. Fourth falls forward, pushes fifth and regains his position. Fifth has no one in front of him and so falls forward without being able to regain his position. This experiment illustrates the alternate compression and rarefaction of the air by the alternate fallings forward and regaining of positions undertaken by the boys. The air is even more elastic than the boys and so forms these waves of motion which we saw traced out by the stylus on the tuning fork.

Now, it is plain that as the rotation of the circular saw increases in speed the pulses become sufficiently rapid to fuse into one continuous musical sound. If the saw were rotated at irregular, con-

stantly shifting speed, the separate shocks would not coalesce, and we should have merely the sensation of a discontinuous, fragmentary, grating series of shocks which we should call a noise. Thus again we see that regularly recurring motions of the sounding body are requisite to produce musical sounds.

Transmission of Sound. But the illustration of the five boys (which is due to the celebrated Professor Tyndall), shows something further. It shows first how the excitation of a body into vibration at regular intervals produces an effect upon the immediately surrounding air, causing it in turn to oscillate back and forth in pulses of alternate compression and rarefaction. But it shows more. It shows that the sound-motion, as we may call it, may be transmitted to any distance through the air, just as the shock started at one end of the row of boys travels to the other end, although each boy moves only a little and at once recovers his position. So also each particle of air merely receives its little push or compression from the one motion of the tuning-fork or string, and transmits this to the next adjacent particle. At the backward swing of the tuning-fork or string each air particle drops back to fill up the partial vacuum it left in its forward motion, thus starting a reversed motion which in turn is transmitted to the next adjacent particle and so on to the ear of the hearer.

Yet each particle has merely oscillated slightly back and forth.

Now, this mode of transmission evidently depends upon the existence of an atmosphere. In fact, we can soon show that, apart from all questions of ears, sound could not exist for us, as we are in this state of existence, without an atmosphere. Let an alarm-clock be set to ringing and then be placed under the glass bell of an air-pump.

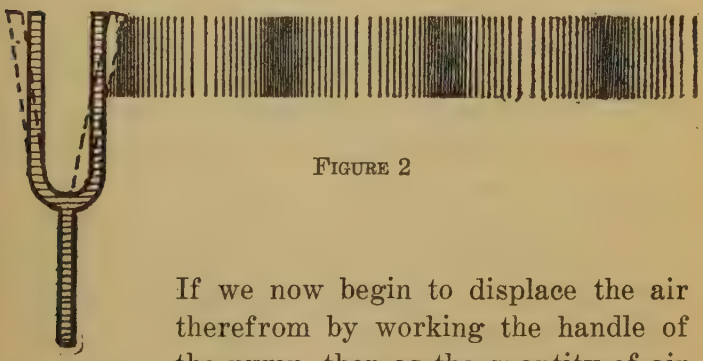

FIGURE 2

If we now begin to displace the air therefrom by working the handle of the pump, then as the quantity of air inside the bell becomes smaller and smaller, the sound of the alarm-clock's ringing becomes fainter and fainter until, where the air is at a certain point of rarefaction, it entirely disappears; although the clapper of the alarm may still be seen working. In other words, there must be an atmosphere or other similar medium, like water, for transmission of the sound-motion from the excited body to the ear, if a sound is to exist, *i. e.*, be heard.

Properties of Musical Sounds. Having arrived at this point, we are now in a position to discuss musical sounds in general and the laws that govern their behavior. The first point to be made is that musical sounds are distinguished from noises by the continuity of their sensation; or in other words, musical sounds are evoked by *periodic* vibrations. It is thus possible to measure the frequency of the vibrations that evoke a sound of some given height; in other words, to determine its pitch.

It is also possible, as we shall see, to determine a second property of musical sounds; namely, their relative loudness or softness, or, as we shall call it, their intensity.

Lastly, we can discover differences in character or quality between musical sounds, and we shall see also that it is possible to measure these differences accurately.

Loudness. Let us begin with the second quality mentioned; that of loudness or intensity. If a tuning fork be excited by means of a violin bow and then examined through a microscope while its motion persists, it will be observed that as the sound dies away, the amplitude or width of swing of the prongs becomes less and less, until a cessation of motion and of the sound occur together. If, whilst the sound is thus dying away, the fork is again bowed, the amplitude of the prong's

motion again is seen to increase just as the sound increases. In fact, it has been found by experiment that not only does the loudness of a sound vary with the amplitude of the vibrations of the sounding body; but exactly as the square of the amplitude. For instance, if a piano string can be made to vibrate so that the width of swing in its motion is one-fiftieth of an inch, and if another piano string giving the same pitch can be made to vibrate with an amplitude of one twenty-fifth of an inch, then the second will have an amplitude twice that of the first and its sound will be four times as loud.

However, let it be remarked that the mechanical operations thus described do not necessarily correspond with what we actually seem to hear. In other words, the sensation of loudness and the mechanical cause thereof do not always agree, for the reason that we do not hear some musical sounds so well as others. For instance, it is well known that sounds of low frequency never seem so loud as sounds of high frequency, even though the amplitude of vibration in each case be the same. A low frequency sound always sounds less loud than it really should be, so to speak, and a high frequency sound louder than it really should be.

There is only one more important point about sound-intensity, namely, that the loudness of a sound varies inversely as the square of the dis-

tance of the sounding body from the hearer. Thus, other things being equal, a sound heard at a distance of fifty feet should be four times as loud as one heard at a distance of twice fifty, or one hundred, feet. However, it must also be remembered that the situation of the sounding body and of the hearer in proximity to other objects, has a modifying effect upon the loudness of sound as perceived. In fact, we shall see that this is only part of the truth expressed in the term "resonance," about which I shall have something to say later on.

Pitch. Without making any special attempt at producing an ideal definition of "pitch," it will be enough to call it the relative acuteness or gravity of a musical sound. Everybody knows what is meant by saying that a musical sound is "high" or "low." It is the task of acoustics to find some measuring-rule, some standard, whereby we can measure this lowness or highness of any sound, and thus place it accurately in relation to all other sounds. The whole system of music is built upon simply a measure of pitch, as we shall see.

Musical sounds are produced through the periodic continuous vibration of some body. In the experiment of the circular saw, to which I directed attention some pages back, it was pointed out that as the speed of the saw increases, so the musical sound produced through its contact with the wood

becomes shriller. This may be verified by any number of experiments that one chooses to make. The net result is the fact that the pitch of musical sounds depends upon the number of vibrations in a given unit of time performed by the sounding body. Let us put it in a formula, thus:

The pitch of a musical sound varies directly as the number of vibrations per unit of time performed by the sounding body; the greater number of vibrations, the higher the pitch.

Unit of Time. It is customary to assign the second as the unit of time in measuring frequency of vibrations, and in future we shall use this always. If, therefore, we speak of a certain pitch as, say, 500, we shall mean 500 vibrations per second.

Double Vibrations. In counting vibrations, we understand that a motion to *and* fro constitutes one complete vibration. A motion to *or* fro would be merely a semi-vibration or oscillation. In the United States and England it is customary to imply a double vibration (to *and* fro) when speaking of a "vibration." In France the single or semi-vibration is the unit of measurement, so that the figures of pitch are always just double what they are as reckoned in the English or American style.

Range of Audibility. It is found as the result of experiment that the human sense of hearing is distinctly limited. The lowest tone that can be

distinctly heard as a musical sound is probably the lowest A (A_1) of the piano which, at the standard international pitch, has a frequency of 27.50 vibrations per second. Sounds of still lower frequency may perhaps be audible, but this is doubtful, except in the cases of persons specially trained and with special facilities. In fact, any specific musical sounds lower than this probably do not exist for human beings, and when supposed to be heard, are in reality not such sounds at all, but upper partials thereof. The 64-foot organ pipe, which has occasionally been used, nominally realises tones lower than 27 vibrations per second, but these are certainly not audible as specific separate sounds. They can and do serve perhaps as a bass to reinforce the upper partials of the pipe or the upper tones of a chord; but they do not appear as separate sounds, simply because the ear does not realise their pulses as a continuous sensation, but separates them. In fact, we may feel safe in concluding that the lowest A of the piano is the lowest of musical sounds generally audible. This statement is made in face of the fact that the sound evoked by the piano string of this note is usually powerful and full. This only means, however, that the sound we hear on the piano is not the pure fundamental vibration of 27.50 vibrations per second, but a mixture of upper partials reinforced by the fundamental. Of these partials we

shall have to speak later, for they are of vital importance to the due consideration of our subject-matter.

A similar limitation confronts us when we come to the highest tones audible by the human ear. Here again there is considerable diversity of opinion as well as of experience. The highest note of the piano, C_{88}, has a frequency of 4185.98 vibrations per second at the 1925 standard pitch. However, there is no special difficulty in hearing sounds as much as two octaves higher, or up to 16,750 vibrations per second. Above this limit, comparatively few people can hear anything, although musicians and acousticians have been able to go much higher.[1]

The Musical Range. The limits of audibility therefore embrace eleven octaves of sounds, but the musical range is considerably smaller. The modern piano embraces virtually the complete compass of sounds used in music, and as we all know, that range is seven octaves and a minor third, from A_1 to C_{88}.[2]

[1] Many years ago before I had become practically interested in acoustics, and when my ear therefore was in every sense untrained, I was tested by the Galton whistle up to 24,000 vibrations per second, which is near F sharp, two and one-half octaves above the piano's highest note. This is well up to the higher limit of most trained ears, although some acousticians have tuned forks running up to C_{124} with 33,500 vibrations per second.

[2] In order to avoid confusion the position of any note in the scale of music will hereafter throughout this book be indicated by placing a subscript number after the name of the note. Thus the lowest bass note of the piano will be A_1, the highest treble note C_{88}. C_{40} is middle C, and so on.

Let it be noted that if the range of hearable sounds lies between, say 27 and 32,000 vibrations per second, the number of possible distinct musical sounds is enormous. We know that it is quite possible for the trained ear to discriminate between sounds which, at the lower end of the gamut anyhow, are no more than 4 vibrations per second apart. For many years the late Dr. Rudolph Koenig, of Paris, one of the most gifted acousticians the world has ever known, was engaged in the construction of a so-called universal tonometer, consisting of a superb set of one hundred and fifty tuning forks, ranging in frequency from 16 to 21,845.3 vibrations per second. In this remarkable instrument of precision, the lowest sounds differ from each other by one-half a vibration per second, while within the musical compass the difference never exceeds four vibrations. It can readily be seen therefore that the number of possible musical sounds is very much greater than the eighty-eight which comprise the musical gamut of the piano.

The question how the musical scale, as we know it, came to be what it is, is really to one side of our purpose,[1] but whatever may have been its origin,

[1] The claims made for the eleventh century monk, Guido d'Arezzo, have been disputed, and the reader who is interested in the historical aspect of the subject is referred to Grove's "Dictionary of Music and Musicians," to Helmholtz' "Sensations of Tone," and to A. J. Ellis' "History of Musical Pitch," quoted in Appendix 20 of his translation of Helmholtz (3rd edition).

we know that the diatonic scale has existed since the twelfth century, although the foundation of what we call modern music, employing the chromatic tempered scale, was rightly laid only by Sebastian Bach, who died in 1750. Music is a young art, as time goes.

The Diatonic Scale. We have already seen that the musical sound[1] is a fixed quantity, as it were, being the sensation that is produced or evoked by a definite number of vibrations in a given time. This being the case, it becomes evident that all musical sounds must bear mathematical relations to each other. As long ago as the sixth century B. C. the Greek philosopher and scientific investigator Pythagoras propounded the notion that the agreeableness of tones when used with each other is in proportion to the simplicity of their mathematical relations. Now, if we look at the scale we use today we find that although the relations of the successive members of it to each other appear to be complex, yet in fact these are really most simple. Let us see how this is:

Unison. We all know that we can recognize one single sound[1] and remember it when we hear it a second time. If now we draw the same sound from two sources we find that the two blend perfectly and that we have what we call an unison.

[1] The word "Note" is used commonly though really incorrectly to designate a musical sound actually forming part of the musical scale.

If we were to designate the first sound by the mathematical symbol 1, we should say that the unison is equivalent to the proportion 1:1. This is the simplest of relations; but it is so because it is a relation between two sounds of the same pitch, not between two different sounds.

Octave. We all recognize also the interval which we call the octave and we know that in reality two sounds an octave apart are identical, except that they exist on different planes or levels. So, if we play the note C and then evoke the C which lies an octave above, we find that we have two sounds that actually blend into one and are virtually one. When we come to discover the relations between two sounds at the octave interval, we find that the higher sound is produced by just twice as many vibrations in a given time as suffice to produce the lower sound, and so we can express this octave relation mathematically by the symbol 1:2. This is a relation really as simple as that of the unison, for the octave to a given sound is simply an unison with one member thereof on a higher or lower plane.

Perfect Fifth. The relation next in simplicity should naturally give us the next closest relation. And we find that the ear at once accepts as the next closest relation what is called the fifth. If one strikes simultaneously the keys C—G upwards on

the piano one observes that they blend together almost as perfectly as the notes C—C or G—G, or any other octave or unison. The interval or relation thus sounded is called a perfect fifth. When we come to trace its acoustical relations we find that a note[1] a fifth above any other note is produced by just one and a half times as many vibrations in a given time as suffice to produce the lower note.

Thus we can place the mathematical relation of the interval of a perfect fifth as $1:1\frac{1}{2}$, or better still, for the sake of simplicity, as $2:3$, which is the same thing. So we now have the simplest relation that can exist between different musical sounds; the relation of the perfect fifth or $2:3$. This important fact will lead to essential results, as we shall see.

The Natural Scale. This interval, the fifth, will be found competent to furnish us with the entire scale which the musical feeling and intuition of men have caused them, throughout the entire western world at least, to accept as the basis of music and of musical instruments; that is to say, the diatonic scale. If we begin with the note C at any part of the compass and take a series of fifths upwards we shall arrive at the scale of Figure 3. These notes, of course, are spread over a compass of five octaves, but if they are drawn together into

[1] Cf. note 1, p. 17.

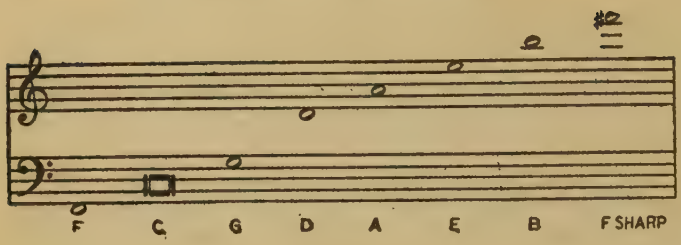

FIGURE 3

the compass of one octave, as they may rightly be drawn (see *supra* "The Octave") then we shall have a scale like this:

C D E F sharp G A B

Now the F sharp in the present case is not actually used, but instead we have F natural, which, in fact, is drawn from the interval of a perfect fifth below the key-tone C. The reason for this preference of F natural over F sharp lies in the fact that the diatonic scale is thereby given a certain symmetry of sound which otherwise it would lack and because the work of practical musical composition is advantaged by the substitution.[1]

The Diatonic Scale. We have arrived now at the Diatonic Major Scale and although we need not here be concerned with the origin thereof, we may be satisfied to know that it appears to satisfy

[1] For a general discussion of these reasons consult Goetschius' "Theory and Practice of Tone-Relations."

the musical needs of civilized mankind. Let us again examine the series of notes, this time including the octave to C, whereby we in reality complete the *circle of fifths,* as it may be called, and return to the key-note, for the octave is the same for musical purposes as the unison. We have then, counting upwards,

C D E F G A B C

which we can readily identify as the series of seven white keys on the piano; with the eighth following and beginning a new series or scale. The complete diatonic scale, when founded on the note C, may thus be seen, merely by looking at the piano, to consist of a series of such scales, seven in all, following one another from one end of the piano to the other.[1]

Relations. Now, if we go a step further and discover the relations which these notes hold to each other mathematically, when brought together into one octave, we find them to be as follows, expressing the lower C as 1 and the upper C as 2, and counting upwards always:

C	D	E	F	G	A	B	C
1	9/8	5/4	4/3	3/2	5/3	15/8	2

[1] The modern piano contains three notes lower than the lowest C, making a minor third more of compass.

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Or in other words, the relation C to D is the same as the ratio 8 to 9. The relation C to E is likewise 4 to 5. The relation C to F is 3 to 4, C to G is 2 to 3, C to A is 3 to 5, C to B is 8 to 15 and C to its octave is 1 to 2.

Tones and Semitones. If we glance at the C scale as shown on the white keys of the piano we shall see that it exhibits some interesting peculiarities. Between each pair of white keys such as C—D or D—E, is a black key, which most people know is called a sharp or a flat. But between E—F and B—C is no space whatever, these pairs of white keys being immediately adjacent to each other. If we run over the keys to sound them we shall find that the sound-interval between E—F or B—C can at once be heard as being smaller or narrower, as it were, than the sound-interval between A—B or C—D or D—E, or F—G or G—A or A—B. The longer intervals, between which we find the black keys, are called diatonic whole tones, and the shorter intervals E—F and B—C are called diatonic semitones.

Diatonic Relationships. The exact relations subsisting between the steps or degrees of the diatonic scale can be ascertained by dividing the ratios previously had, by each other, pair to pair. Consulting the table previously given, showing the relations of the steps to their key-note, we find that when the ratios are divided pair by pair we

get the following relations between each pair of notes:

C.....D....E..F.....G....A.....B..C,
8:9 9:10 15:16 8:9 9:10 8:9 15:16

Now the first thing that will be observed is that there are three intervals here, not two. There are, in fact, evidently two kinds of whole tone or whole step. For it is evident that the sound-distance between C and D is more than the sound-distance between D and E. In actual fact, these two whole steps must be recognized as distinct. This, however, brings about an entirely new condition and one quite unsuspected. For inasmuch as the diatonic scale must of course always retain the same relationships among its successive steps, it is evident that this idea of two different kinds of whole step must land us in difficulties.

The trouble is that we cannot always play in the key of C, by which I mean that sometimes, in fact, very often, we desire to build our music upon diatonic scales which are founded upon other notes than C. From the point of view towards which I am leading—namely, that of tuning—we see here a serious difficulty, for it is at once evident that if we undertake to tune a diatonic scale, as suggested some time back, by considering it as a circle of fifths, we shall get into deep water as soon as we quit the key of C. Let me make this plainer.

Understand first of all that we have as yet talked

only of a scale founded on C and therefore including what are known simply as the white keys or natural notes. Suppose we begin by tuning a series of fifths quite perfect, from some given C, say for the sake of convenience a C of which the pitch is 64 vibrations per second. This is a little less than the pitch of C would be at the 1925 standard, but is more convenient for purposes of calculation.

Then we should get a result like this:

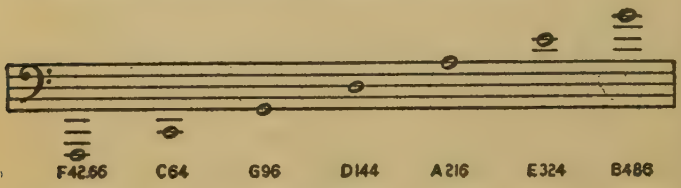

FIGURE 4

Now, let us reduce this down to one octave, by transferring the higher tones down, through the simple process of dividing by 2 for each octave of transference down and multiplying by 2 for each octave of transference up. This will give us the following result:

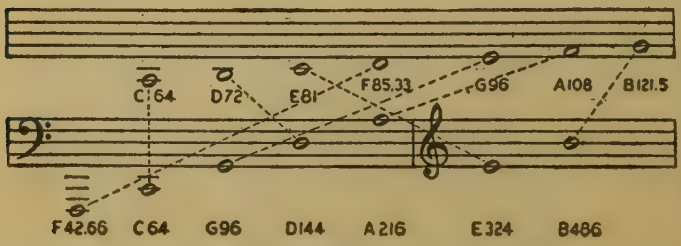

FIGURE 5

Gathering this together, we have the following scale founded on C 128:

C	D	E	F	G	A	B	C
128	144	162	170.66	192	216	243	256

Now, suppose we want to play a tune based on another key-tone than C. Suppose, for instance, that we want to use D 144 as the basis of a scale; that is to say, we want to play in the key of D, as we say. The first thing to do is to find out whether we have notes tuned already which will give us such a scale. Going on the same plan as the pattern diatonic scale of C, already worked out, and applying it to D, we find that we need the following notes:

D E F♯ G A B C♯ D

All of these we already have except F♯ and C♯. We can get F♯ by tuning a perfect fifth above B 243, which will give us F♯ 364.5. Dropping this an octave we have F♯ 182.25. C♯ is a perfect fifth above F♯ and so will be 546.75, or, dropping an octave, 273.375. Now, we can construct a scale of D as follows, beginning with the D 144 that we already have, using all the other notes already provided and the two new ones besides. That gives us:

D	E	F♯	G	A	B	C♯	D
144	162	182.25	192	216	243	273.375	288

If you will look at it closely you will see that there must be something wrong. The distance between F♯ and G seems small, and so does the distance between C♯ and D. To test the thing, let us now construct a diatonic scale on the ratios we know to be correct[1] and see what results we get. It works out as follows:

D	E	F♯	G	A	B	C♯	D
144	162	180	192	216	240	270	288

Ratios

8:9 9:10 15:16 8:9 9:10 8:9 15:16

Now, just for purposes of comparison, let us put these two scales together, one below the other. They look like this:

SCALE MADE UP FROM C SCALE AND PERFECT FIFTHS TUNED THEREFROM

D	E	F♯	G	A	B	C♯	D
144	162	182.25	192	216	243	273.375	288

SCALE MADE UP FROM KNOWN DIATONIC RATIOS

144	162	*180*	192	216	*240*	*270*	288

At once it can be seen that the F♯ and the C♯ which we manufactured by the perfectly legitimate method of tuning perfect fifths from the nearest tone available in the scale of C, are both wrong when secured in this way. Also, it can be seen that the B which belongs to the scale of C will not do for the scale of D. Not only is this so, but if the experiment is made with other key-notes, it

[1] See page 21 et seq.

will be found that they all, except the scale of G, differ somewhere and to a greater or less extent from the scale of C, even with reference to the notes which they have in common with C.

True Intonation. It is evident, therefore, that no method of building up diatonic scales by tuning pure intervals, will do for us if we are going to use the same keys and the same strings for all the scales we need. It is evident, in fact, that if we tune perfect fifths or any other intervals from C or any other key-note and expect thereby to gain a diatonic scale that will be suitably in tune for all tonalities[2] in which we may want to play, we shall be disappointed. Not only is this so, but it must be remembered that so far we have not attempted to consider any of the so-called sharps and flats, except in the one case where we found two sharps in the diatonic scale of D, properly belonging there. It turns out, however, when we investigate the subject, that the sharp of C, when C is in the scale of C, is quite a different thing, for instance (as to pitch), from the C♯ which is the seventh note of the scale of D.

Chromatic Semitone. The chromatic semitone, which found its way into the scale during the

[2] The word "tonality" is used to signify a scale founded on any key-note. The scale of C, founded on C, is a "tonality," the scale of F♯ is another "tonality" and so on. The use of this word enables us to avoid the confusion that might arise from the use of the word "key" in this significance.

formative period of musical art—mainly because it filled a want—is found upon investigation to bear to its natural the ratio $^{24}/_{25}$ or $^{25}/_{24}$, according as it is a flat or a sharp. In the case we have been considering, then, while C♯ as the seventh note in the diatonic scale of D has a pitch, in true intonation, of 270, the C♯ which is the chromatic of C 256 (see previous tables) would have a pitch of $256 \times {}^{25}/_{24}$ or 266.66. Similar differences exist in all cases between chromatic and diatonic semitones, thus introducing another element of confusion and impossibility into any attempt to tune in true intonation.

Derivation of Chromatic Ratio. Actually the chromatic semitone is the difference between a $^{10}/_{9}$ ratio whole step, or "minor tone" as it is often called, and a diatonic semitone; thus $^{10}/_{9} \div {}^{16}/_{15} = {}^{25}/_{24}$.

The Comma. The difference between the $^{9}/_{8}$ (major) and the $^{10}/_{9}$ (minor) tones (whole steps) is called a "comma" $= {}^{81}/_{80}$. This is the smallest musical interval and is used of course only in acoustics. ($^{9}/_{8} \div {}^{10}/_{9} = {}^{81}/_{80}$.)[1]

Musical Instruments Imperfect. The above discussion, then, leads us to the truth that all musical instruments which utilize fixed notes are necessarily imperfect. As we know, the piano, the organ

[1] The diatonic minor scale is affected equally by this argument; but has not been mentioned here for reasons set forth in Chapter III.

and all keyed instruments are constructed on a basis of seven white and five black keys to each octave, or as it is generally said, on a 12-to-the-octave basis (13 including the octave note). If now we are to play, as we of course do play, in all tonalities on this same key-board, it is evident that we cannot tune pure diatonic scales. The imperfection here uncovered has, of course, existed ever since fixed-note musical instruments came into being. The difficulty, which has always been recognized by instrument builders and musical theorists, can be put succinctly as follows:

The piano and all keyed instruments are imperfect, in that they must not be tuned perfectly in any one scale if they are to be played in more than that one scale. Hence a system of compromise, of some sort, must be the basis of tuning them.

The violins and violin family, the slide trombone and the human voice can, of course, sound in pure intonation, because the performer can change the tuning from instant to instant by moving his finger on the string, modifying the length of the tube or contracting the vocal chords. When any of these, however, is played together with keyed instruments, the tuning of these true intonation instruments is always of course modified (though unconsciously), to fit the situation.

All Tuning Imperfect. All tuning, therefore, is necessarily imperfect, and must be based upon

some system of compromise. The system now universal is known as the Equal Temperament. Other systems of unequal or mean temperament have been used, as will be explained later on, but the Equal Temperament has superseded them all.

Temperament. I have taken the reader through a somewhat lengthy explanation of the inevitability of a system of temperament, on the notion that thereby he may be able to understand for himself, from the beginning, the necessity for doing things that otherwise would seem illogical and inconsistent. The peculiar kind of tuning that the piano tuner must do would seem in the highest degree absurd to anyone who should not understand the reasons for doing what actually has to be done. Seeing also that this correct knowledge is seldom given by those who teach the practical side of the art, I thought it better to go into some detail. In any case, it is well to realize that no man can possibly be a really artistic piano tuner unless he does know all that is contained in this chapter and all that is contained in the next three. It is worth while, therefore, to be patient and follow through to the end the course of the argument set forth here.[1]

[1] A complete discussion of the problem of true or just intonation is to be found in the classic work of Helmholtz, to which the reader is referred. See especially Chapter XVI, Appendices 17 and 18 and the famous Appendix 20, composed by the English translator, A. J. Ellis.

Chapter II

ON THE VIBRATION OF A PIANO STRING

Of all sounding bodies known to music, the musical string is without doubt the most common, the most easily manipulated for musical and mechanical purposes, and the most efficient. Acquaintance with ascertained facts as to the behavior of musical strings under practical conditions is necessary for the complete equipment of the piano tuner; although this acquaintance need not be exhaustive, so long as it be, to its extent, exact. Avoiding mathematical symbols which, requisite as they are to a comprehensive study of acoustics, may nevertheless be beyond the familiarity of most of those who will read this book, I shall here briefly investigate certain properties of musical strings and especially of the piano string. The discussion, I can promise, need seem neither dry nor uninteresting.

The String. To be exact, a string should be defined as a perfectly flexible and perfectly uniform filament of solid material stretched between two fixed points. But such a string, it must be observed, can exist only as a mathematical abstraction, since neither perfect uniformity nor perfect

flexibility can be expected in strings made by human hands. A string of given flexibility becomes more flexible, as to its whole length, if that length be increased, and, conversely, stiffer as its length is decreased. The property of weight also fluctuates in the same way. Likewise if the force whereby a given string is stretched between two points be measured by a given number of pounds, the effective tension equivalent thereto will of course be decreased if the string be lengthened; or, conversely, will be increased if the string be shortened. A string 12 inches long stretched with a weight of 10 pounds is subjected to a lower tension than is a 6-inch string of similar density and thickness stretched with the same weight. These allowances and corrections, obvious as they are, must constantly be kept in mind if we are to understand the behavior of practical strings, since all the acoustical laws which govern such behavior must be modified in practice according to the facts disclosed above.

Simple Vibration. We have learned that musical sounds owe their existence to the fact that some solid body is thrown into a state of periodic vibration. The kind of vibration can best be explained by likening it to the swing to and fro of a pendulum. A pendulum is fixed at one end and tends naturally to swing back and forth on its pivot. The kind of vibration which the pendulum performs is

called simple or pendular vibration. The tuning fork, when set in vibration, is also very much the same thing as a pendulum, since one end of each prong is fixed and the other end can therefore swing freely. The tuning fork furnishes, when excited, an excellent practical example of simple or pendular vibration of sufficient rapidity to produce musical sound.

Tones of the Piano String. Go to a piano and strike one of the low bass keys in the octave between A_1 and A_{13}. These very low keys operate on single strings only and hence are excellently adapted for our purpose.[1]

Strike on the piano the key, say, F_9, hold the key down, and listen carefully. At first you will hear simply the full sonorous tone F, deep and solemn. But listen closely, repeating the experiment till the ear becomes familiar, and you will gradually observe that, mingled with the original sound F, there are a number of other sounds, apparently very closely related to the original, coloring it rather than altering its pitch, but at the same time recognizable as sounds that spring from a different level. By repeating the experiment with vari-

[1] Incidentally, let me say that the piano is an almost complete ready-made acoustical instrument for the investigation of the phenomena of musical strings, sympathetic resonance, beats and beat-tones, and partials. With a piano at hand the student can dispense with all experimental means except the tuning-fork. I shall suppose that a piano is at hand during the reading of this and other chapters.

ous of these low strings (or by going higher and taking care that one string in the two-string unisons is damped off), you will gradually be able to perceive the remarkable fact that every piano string produces a sort of compound tone, consisting primarily of its natural tone or "fundamental," as we may call it, but containing also the octave thereto, the fifth above that and the second octave. It is true that these extra sounds are feeble and can be heard only with practice and by the exercise of patience; but heard they can be, more and more clearly as one's familiarity with the process grows.

Partial Tones. The truth is that the piano string does not evolve a simple but an exceedingly complex, musical tone. Not only the three extra tones of which I spoke before can be proved to exist, but in fact an immense number of other tones, all bearing given harmonic relations to the fundamental, can be shown to be evoked, and by the use of suitable apparatus can be detected and isolated, one by one, through the sense of hearing. Special resonators have been made which enable the hearer to detect these partial tones clearly. Even without such special apparatus, however, we can detect a number of the partial tones if we take advantage of the piano's property of sympathetic resonance; a property imparted by the sound-board.

Sympathetic Resonance. Hold down the C_{40} key, without striking the string. Then, while holding the key down, strike a powerful blow on the C_{28}, immediately below. When the sound has swelled up, let go the lower key whilst holding on to the upper or silently pressed key. At once the sound of C_{40} floats out of the silence, pure and ethereal. What is the cause of this sound? How has the C_{40} string been excited? The answer is found in the fact that the lower string which was struck, not only produces its fundamental tone but also evokes its octave above. The peculiar sort of vibration of the C_{28} string which produced this octave is résonated through the sound-board and reproduced on the C_{40} string. In the same way, the twelfth (G_{47}) can be brought out, and so can the next octave, C_{52}. In fact, with a very good piano and by choosing a low enough sound for the fundamental, several higher partial tones can thus be brought out by sympathetic resonance from the original string to the string corresponding with the true pitch of that partial.[1]

Complex String Vibration. Thus we learn that the piano string vibrates as a complex of vibrations, not as one simple form of vibration; for it is evident that if the string evokes, as we know it does, a complex of sounds, these must arise

[1] For a further discussion of sympathetic resonance, see Chapter VII.

from a complex of vibrations. Let us see how this is.

Turning again to the piano, we select a string in such a position that it can be measured accurately as to its speaking length. A grand piano is most convenient for the purpose, and the string may be selected from the overstrung or bass section. Now we accurately measure the speaking length of the string between bridges, and mark carefully with a piece of chalk on the sound-board the exact middle point as near as we can determine it. Then we sound the string and whilst holding down the key, touch the string at the middle point very lightly with a feather. If we perform the operation skilfully enough, we shall find that instantly the fundamental tone of the string ceases and there floats out the octave above, quite alone and distinct.

We measure now one-third of the length, mark it, and again sound the string. Placing the feather carefully at the exact division point and damping the shorter segment with a finger, we hear the fifth above the original sound.

Automatic String Division. What is the meaning of all this? Plainly in the first case it means that the string naturally subdivides itself into two parts of equal length and that the vibration of either half gives the octave above the original. Thus we have two vitally important facts at our

disposal, one relating to the form of vibration of the string and the other to the law of string length as proportional to pitch.

Moreover, in the second case, if we allowed the $\frac{1}{3}$ division of the string to vibrate, we should get from it a sound an octave above the sound of the longer or $\frac{2}{3}$ division. Since we damped the shorter segment, however, we conclude that the fifth above the original sound was produced by a string length $\frac{2}{3}$ of the original length. If we now continue our experiments we shall find that $\frac{4}{5}$ of the original length produces a major third above the original sound, and that $\frac{1}{4}$ of the length produces a sound 2 octaves above the original sound. Plainly then, we have two great laws revealed. The first is:

When a string fixed at each end like the piano string, is struck at one end, it vibrates in a complex form, most strongly in its full length but also perceptibly in segments of that length such as $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$.

The second law is equally important. It may be stated as follows:

Length and Pitch. The pitch of a string—that is to say, the number of vibrations, per unit of time which it can perform, is proportional inversely to its length. Thus, since an octave above a given sound has twice as many vibrations per second as the original sound, it follows that to obtain

a sound an octave above a given sound we must have a string one-half as long.

Weight, Thickness and Tension. Similar laws exist with regard to the influence upon string vibrations, of weight, thickness and tension. Without undertaking to prove these completely, we may state them briefly as follows:

The frequency of a string's vibration is inversely proportional to the square root of its weight. In other words, if the weight be divided by 4 (the square of 2) the frequency will be multiplied by 2. To produce a tone one octave above the original tone the weight of the string must be only ¼ its original weight.

The frequency of string vibrations is directly proportional to the square root of their tension. In other words, to get twice as many vibrations, you must multiply the tension by $2^2 = 4$. To get 4 times as many vibrations you must multiply the tension by $4^2 = 16$. So if a string be stretched with a weight of 10 lbs. and it is desired to make it sound an octave higher, this can be done by making the stretching weight ($4 \times 10 =$) 40 lbs.

The frequency of string vibrations is inversely proportional to the thickness of the string. If a string of a given length and weight produces a sound of a given number of vibrations, a string of the same length and of twice the thickness will

give a sound one octave lower; that is, of half the number of vibrations.

Mechanical Variable Factors. All these laws, be it remembered, are based upon the assumption of mathematical strings, in which weight and stiffness remain constant throughout all changes in length. In the case of the actual piano string, in which the weight and tension do vary with the length, some compensation must be made when calculating. Thus, to illustrate, it is found that whereas the acoustical law of frequency of vibration requires a doubling of the string length at each octave downwards, or halving at each octave upwards, the practical string, where weight and tension vary with length, requires a proportion of 1:1.875 instead of 1:2. This difference must be kept in mind.[1]

Why Strings Subdivide. Before, however, we go on to consider the influence exerted, through the peculiar manner in which strings vibrate, upon the problems of tuning and tone-quality, we must take the trouble to discover why they should, in fact, vibrate in this rather than in some other way. It is easy to talk about string subdivision and partial tones, but there is very little use in mouthing words that do not carry with them to our minds real meanings, or in talking about processes which

[1] For a discussion of this point, see my "Acoustic Design and Construction of the Piano," Cap. 2. This book will hereafter be referred to in the notes as "Acoustic Design."

we do not really understand. So, let us take the trouble to discover why a string vibrates as we have shown it to vibrate. Here again the piano shall be our instrument of investigation.

The Wash-line Experiment. The first thing to realize when we begin to talk about string vibrations is that the vibration itself is merely the transmission of a motion from one end of the string to the other. This motion will continue until it is transformed into some other sort of energy or else is thrown out of its direction into another direction. Suppose that we take a long cord, like a wash-line, and as much as twenty feet long. We fasten one end to a post and stretch the cord out until we hold the other end in the hand with the entire length fairly slack. Now we try to jerk the cord up and down so that we can get it to vibrate in one long pulse. This pulse will affect the entire length of the cord, which we shall now observe to rise from its plane of rest, belly out in a sort of wave, descend to the point of rest again, belly out once more on the opposite side and return to the point of rest, making a complete swing to and fro. Compare the illustration Figure 6.

When we find that we can do this (practice is needed), we make a different experiment. We now try to jerk the cord with a sort of short sharp jerk so that, instead of its vibrating in its whole length, a sort of hump is formed on it which travels like

a wave traveling through a body of water. This short wave travels along the whole cord, as we see by watching it narrowly, until it comes to the end fixed on the post, when at once, instead of disap-

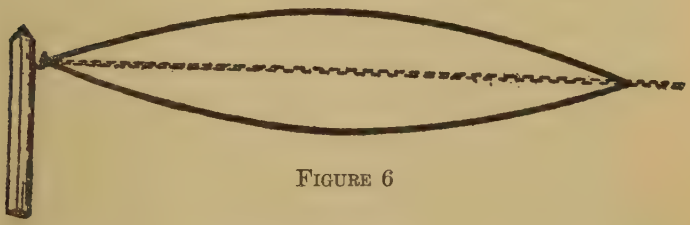

FIGURE 6

pearing, it is reflected, reversing its direction of travel and also its position, being now on the opposite side of the cord. Thus reflected, the short wave travels back towards us.

This is an example of what is called the *reflection* of a sound impulse. It has a very important bearing on the general problem of piano string vibration, as we shall see.

Suppose that we can time our efforts so carefully that we deliver a series of these short sharp jerks, forming these short waves, at the rate of one per second. Then we find that the second impulse starts away from the hand just as the first impulse starts back from the fixed end of the string. The two impulses, traveling in opposite directions and in opposite phases of motion (i. e. in positions on the cord opposite to each other), will meet precisely in the center, for neither one

can pass the other. At their meeting place, the exact middle of the string, the forces are equal and opposite, so that a *node,* or point of greatly diminished amplitude of motion, is formed. The two pulses therefore have no option but to continue vibrating independently, thus dividing the string into two independently vibrating halves, each of double the original speed. See the illustration, Figure 7.

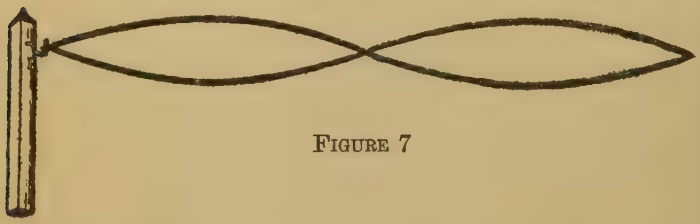

FIGURE 7

Meanwhile a second impulse from the hand begins to travel along the cord. When it meets the already segmented halves, there is a further reflection and subdivision. This again continues still further at the next impulse, so that finally, if the impulses can be kept up long enough, the result will be the division of the cord into four, five, six, and up to perhaps ten of these "ventral segments," separated by nodes.

Harmonic Motion. This being the mode of vibration of slow moving cords, we can see how the rapidly moving piano string must always be thrown into an exactly similar state of complex

vibration; for we must remember that not only is its vibration very rapid, ranging from 27 to more than 4100 vibrations per second, but also that there is no limit to the possible number of subdivisions. Moreover, the piano string is very stiff, and since it is fixed at both ends and excited by a sharp blow, its motion is not only rapid but powerful, so that the reflections are unusually strong and numerous. Hence the wave of motion of the piano string is remarkably complex.

Resultant Motion. This entire complex motion of the piano string is of course the result of the operation of many forces, moving from different directions, upon a single resistance; so that the effect of the interference of the forces with each other is that their net efficiency works out in some direction which is a resultant of all the directions. Thus, the piano string, if it be examined under motion by any optical method,[1] is seen to vibrate in a wave motion which is the resultant of all the partial motions. The general appearance of such a wave is as shown in the illustration, Figure 8, which gives (theoretically) the resultant of a wave motion including subdivision into six segments.[2]

[1] As by the Phonodeik or the Osiso.

[2] This illustration is after the original by the late Prof. A. M. Mayer, of Stevens Institute, whose drawings of harmonic curves and resultants were first published in the Philosophical Magazine for 1875. In order to show clearly the six separate wave motions, their respective amplitudes have been made proportional to wave length. This is of course a scientific fiction, but the effect upon the resultant curve is not markedly distorting.

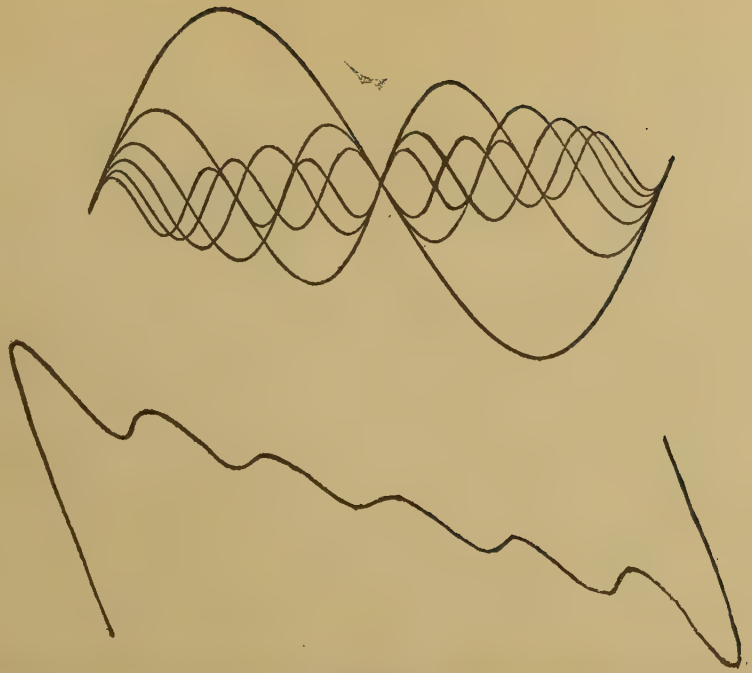

FIGURE 8

The piano usually has the first twelve and often the fourteenth, in the lower and middle registers, and still higher partials in the high treble, but the latter can hardly be isolated without special apparatus; and then not easily. Of course, as we shall see later, there are certain causes which affect the form of the wave in the piano string, in practical conditions, and so modify the series of partials.

Fourier's Theorem. One of the greatest French mathematicians, Fourier, investigating another subject altogether, discovered the law of this harmonic motion of a string when he showed that every complex vibratory motion can be reduced to a series of simple pendular motions, of which the terms are as follows:

1, ½, ⅓, ¼, ⅕, ⅙, ⅐, ⅛, ⅑, 1/10, etc. *ad infinitum.* In other words, the very subdivision of the piano string into segments is here shown mathematically to be the necessary basis of all compound motion in vibrational form. Thus mathematics, from another angle, amply confirms the ideas above set forth.[1]

Partial Tones. The string then, vibrates in its whole length, its ½, ⅓, ¼, ⅕, ⅙, ⅐, ⅛, and in smaller segments indefinitely. The whole-length vibration produces the fundamental tone of the string. The ½ gives twice as many vibrations, or

[1] J. B. Fourier, 1768-1830, author of "Analysis of Determinate Equations." Compare my "Acoustic Design," where the Fourier equations are reproduced and discussed.

the octave above. The ⅓ gives the twelfth, and the ¼ gives the double octave. Thus, the piano string C 64, when sounded, actually involves not only the fundamental tone, but all the following:

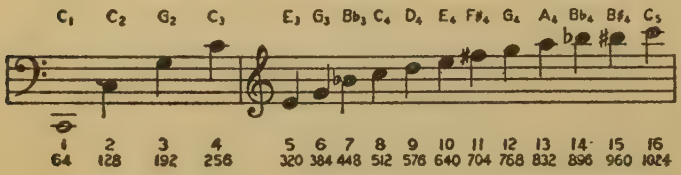

FIGURE 9

and many more not shown. All these are called partials. The fundamental is the first partial, the octave is the second, and so on. Above the tenth, although the number of possible subdivisions is unlimited, the pitch becomes less and less definitely referable to any specific note of the scale. The first 6 partials, as can be seen, are simply the common chord of C spread out. The 8th, 10th, 12th and 16th are octaves to the 4th, 5th, 6th and 8th. The 7th is flatter than the diatonic 7th which we use, although the former is the natural tone and the latter quite artificial.[1] The other odd-numbered partials are all more or less out of tune with their nominal equivalents, until, at a short distance above the 16th, all pretence of consonance except in the 20th, 24th and 32nd, has vanished.

[1] Cf. Chapter I, "Natural Scale."

Influence of Partials. It should be remembered that, although all the odd and most of the even-numbered partials above the 10th are dissonant and this dissonance progressively increases—if one may use the term—the number of partials that may occur above the 10th in a piano string is quite large. This being the case, it will be understood that although these partials are relatively feeble and their sounds do not affect the general sensation of pitch, they do have another effect; and this is felt in what is called the "quality" or "color" of the sound. In fact, as we shall soon see, the harshness or mellowness, thinness or fullness, of a sound, as evoked from the piano, not to mention the greater characteristic differences which distinguish the tone of one instrument from that of another, are all to be attributed to the manner in which the various partials are mixed with the fundamental.

Series of Partials. But why should there be from one piano string a mixture of partial tones different from that which persists in another? For that matter, since the tendency of other sonorous bodies, like pipes for instance, is to divide up naturally into ventral segments, like strings, why should not all tone qualities be alike? Obviously the difference must arise because one wave form varies from another; or in other words because one string or pipe or rod produces one

specific mixture of partials and another a different mixture. Why this should be so in the case of the piano string, which is our present concern, I shall now explain, and the following discussion will be of great assistance in promoting an understanding of some most important problems.

Point of Contact. The piano string is excited by a more or less violent blow from a felt-covered hammer. The impulse thus given to the string is relatively powerful, and its effect upon the highly tensioned filament of steel is such as to induce instant reflection of the sound-impulse and subdivision of the string into ventral segments. The identity of the individual segments into which the subdivision takes place is mainly determined by one special condition; namely, by the position of the hammer's point of contact. As will be remembered, the segments of the string are separated from each other by points of apparent rest called nodes. Of course, these nodes are not actually at rest, but the amplitude of their motion is greatly restricted by reason of the opposed forces pulling from each side upon them. If now the exciting blow is struck exactly on one of the nodes, the vibration of the shorter of the two segments into which that node divides the string, and equally the vibrations of all multiples thereof, will be blotted out. Thus, if we wish to eliminate the 7th partial, we must strike exactly on the 7th node,

that is to say at exactly $1/7$ of the string's speaking length. It is obvious that since the first six partials are simply components of the common chord of the fundamental or 1st partial, and the 8th is triple octave thereto, the elimination of the 7th will produce a perfectly harmonious flow of partials and in consequence a full round mellow tone. Experience confirms this deduction, although the exigencies of piano building usually compel a striking distance, as it is called, positioned at $1/8$ or even higher for the greater number of the strings, and running progressively higher in the upper treble till it reaches $1/16$ at the extreme C_{88}. The influence of contact point position is thus clearly shown, for if any of the very high strings be purposely struck at lower points than the hammers are fixed to strike them, it will be found that their tone is less bright, more mellow, and even feebler. The last quality is due to the fact that the prime or 1st partial of these short stiff strings is the only component which comes out at all powerfully. The resulting sound is therefore not sufficiently rich in upper partials. Striking points are changed towards one end of the strings in this region in order to encourage the production of upper partials. It might be remembered incidentally that in the two highest octaves of the piano the progressively higher contact points of the hammers on the strings signify this purpose,

which, however, is imperfectly, if at all, attained thereby. But the longer and more naturally powerful strings are struck at about ⅛ of their distance and sometimes are better off when struck at ⅐.

Material. The properties of the material from which the string is made are also of importance in considering the precise nature of the mixture of partials which any given example may show. The stiffer a string is, other things being equal, the less rapid and complex will be the reflections of wave-motion and the consequent formation of ventral segments. Now the piano is peculiar in that the tension of its strings does not vary from one end to the other, so greatly in proportion as does the thickness, since even in the understrung part of the scale the difference between the extreme treble and the first above the overstrung will usually be something like the difference between 5 and 8. So it follows that the upper treble strings are very much stiffer than those in the lower regions, in proportion to their length. Of course the length factor enters into the complex here too, for higher strings are shorter, and so again stiffer, for any given stretching force.[1]

Simultaneous String Vibrations. We shall now have to face the last and in some ways the most

[1] See my "Acoustic Design" for a complete discussion of the piano string problem in all its phases.

fascinating of all the subjects which we shall confront in the course of our examination into the vibrations of the piano string. So far we have confined our thought to individual strings sounding alone. We now have to consider the very beautiful and important phenomena arising from the evocation of two sounds simultaneously. The inquiry is of the utmost importance in the higher analysis of piano tuning.

Beats. The piano serves us again to good purpose in examining the behavior of simultaneously evoked sounds. Let us damp off one string in a triple unison on the piano. (All strings of the modern piano above the overstrung section are strung with three strings to the note.) This will leave two strings vibrating. If the piano has not been tuned very recently, it is almost certain that when we listen carefully to these two strings we shall hear a sort of sound that can only be described as discontinuous and "wavy." In order to make sure suppose we choose the strings corresponding to $C_{40} = 261.6$ (middle C at the 1925 pitch). Let us damp one string of the triple and then slightly turn the pin of one of the others so as definitely to put it out of tune with its fellow. A very slight turn, just enough to feel the string give, will be sufficient. Now, take a tuning fork sounding exactly the same 1925 standard pitch $C_{40} = 261.6$. Sound it and listen carefully. You

will hear a clear continuous tone, which persists without deviation or fluctuation. Put aside the tuning fork, strike the piano key, and listen. By contrast you hear a confused medley of sound, in which the fundamental pitch is discernible, but is surrounded by, and buried in, a mass of wavy, fluctuating, rising and falling sounds of a peculiar character, which are unmistakable when once heard, The peculiar character of these sounds is their rise-and-fall effect. The tone swells out far beyond its normal intensity and then dies away. This wave-like sound rises and falls at definite intervals, and it will be seen that the farther apart in pitch the two strings are, the more of these rise-and-fall periods there will be in a given time. If now we begin to turn the tuning-pin backward, so as to bring the disturbed string again to its original equality of pitch with the other, we shall find that the wavy sounds gradually become slower and slower, until at length they disappear, and only the pure continuous unison-like sound remains; showing that the two strings have now been brought into perfect accord. Let us see what causes this interesting phenomenon.

Condensation and Rarefaction. We must go back for a few moments to some earlier considerations. A sound-wave is an oscillation to and fro. When a tuning fork prong vibrates, the first half of the vibration is when the prong moves away

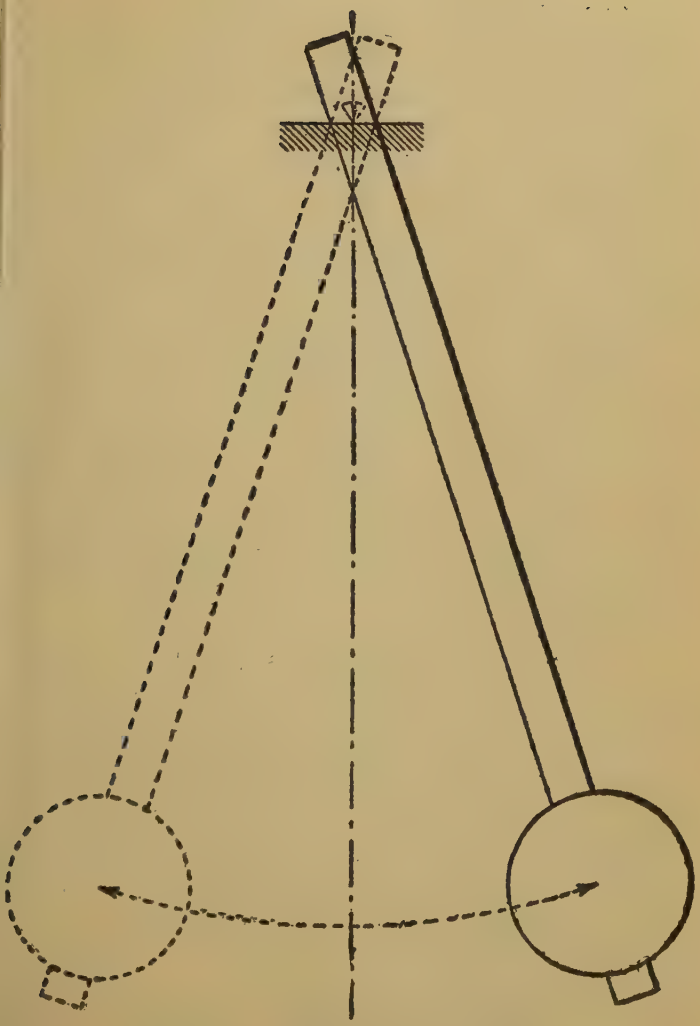

FIGURE 10

from its position of rest and pushes the air in front of it against the surrounding air. This part of the vibration has the effect of compressing the air on that side, whilst on the other side the air moves forward to fill up the vacuum left by the moving away of the prong and thus is rarefied or thinned. Consider a vibrating pendulum (Fig. 10), and think of it as if it were a slow moving tuning fork. As the pendulum moves in one direction it condenses or compresses the air in front of it, and then as it moves back, the same air is again rarefied, or thinned out to its original density; for air is elastic and rebounds. Thus each complete vibration of tuning fork, string, or pendulum, no matter how slow or rapid, produces a condensation followed by a rarefaction of the surrounding air.

Wave-length. The space or distance between one condensation and the next, or between one rarefaction and the next, is called the wave-length. The more of these pulses there are in any unit of time, the shorter the length of each. Sound travels at the rate of 1100 feet per second, roughly speaking. The wave-length of a tone of 100 vibrations per second therefore is $^{1100}/_{100}$ or 11 feet. Figure 11 illustrates this point.

FIGURE 11

Phase. Thus we see that a sound-wave propagated through the air consists of a series of these oscillations of rarefaction and condensation. Now suppose that we start two such wave systems simultaneously from two things perfectly in tune. We start them exactly at the same time, so that the condensations begin together. A good example would be the striking of two strings at once on the piano, when the two sets of vibrations will run exactly together, condensation with condensation, and rarefaction with rarefaction, as is shown by Figure 12. When running thus together, the two waves are said to be in the same phase.

FIGURE 12

Difference of Phase. Now suppose we can arrange to start one string vibrating just half a complete vibration behind the other. Then, condensation of No. 2 begins simultaneously with the first rarefaction of No. 1, and we have the state of affairs pictured in Figure 13. Such a condition is called "difference of phase."

FIGURE 13

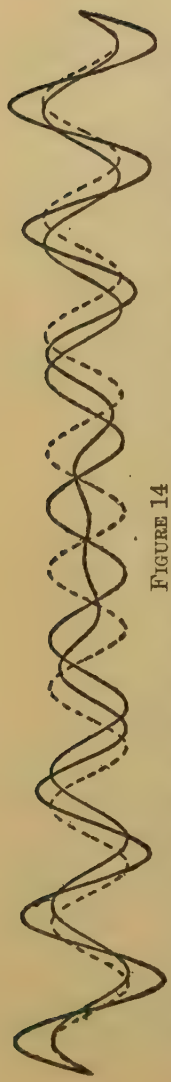

FIGURE 14

Difference of One Vibration. Suppose two piano strings, one of which gives just one vibration less per second than the other. Now, when these two strings are sounded simultaneously, it follows that at the end of a whole second one will be exactly one vibration behind the other. Likewise, at the end of half a second one will be half a vibration behind the other; or in other words, at the end of half a second, or right in the middle of one second's complete series of vibrations, the two will be in different phases, while at the end of a whole second they will have regained identity of phase; will be in the same phase together again. Suppose now we lay out on paper two wave systems, whose frequencies, for the sake of simplicity, shall be in the ratio 8:9. Let us also show, by a third wave-curve, the result of the simultaneous activities of the two waves. In order to avoid a complex drawing I show just eight vibrations of the one and nine of the other. These will consequently begin and end together.

Resonance and Interference. Now as soon as we examine these superimposed curves, we shall see that at the second complete vibration they are distinctly out of step with each other, and that by the time one has made four complete vibrations they are in definitely opposite phases. From this point onwards the difference subsides, until at the eighth vibration of the one and the ninth of the other, the phase is again the same for both.

Now it will at once be seen that when the two waves start, two condensations come together, so one reinforces the other, which of course means an increase in amplitude of the combined sound. Hence at the beginning of the waves the loudness of the combined sounds will be intensified above the loudness of either of them alone. We have a condition of resonance, as it is called.

On the other hand, when the middle of the curve has been reached, we see that the condensation of one meets the rarefaction of the other exactly, so that at this point the one wave blots out the other, and produces a perfect "interference" as it is called, momentarily cancelling the sound altogether.

Hence we have the rise and fall of sound which we heard so clearly in the two piano strings mentioned above. This rise and fall is very distinct, and in the present case would occur at each 8-to-9 period; in other words, if the two waves were

vibrating at 80 and at 90 vibrations per second respectively, there would be heard 10 beats per second between them when sounded together.

Frequency of Beats. Beats therefore arise between sounds nominally in unison but actually slightly out of tune with each other. The number of beats in a given time is equal to the difference between the frequencies of the generating sounds.

Coincident Partials. Beats arise only between unisons. When heard in such intervals as the octave, fifth, fourth, third and others, this is because partial tones which may be common to both are thrown out of tune slightly; and the beats arise between them. For instance, the beats in an octave which is somewhat out of tune arise between the prime of the upper tone and the second of the lower; which are the same. Example: if $C_1 = 64$ then $C_2 = 128$. Prime of the higher is 128. Second of the lower is 128. These are also coincident, and if the strings which produce the primes are not in accord, the coincident partials will generate beats as above. The same is true in the interval of a perfect fifth, where the coincident partials are the second of the higher and the third of the lower. Let us note that the coincident partials always bear the same numbers as express the ratio of the fundamentals. Thus the octave ratio $= 1:2$ and the coincident partials

are 2 and 1. The fifth ratio = 2:3 and the coincident partials are 3 and 2. The fourth ratio = 3:4 and the coincident partials are 4 and 3; and so on for all other intervals. For instance: Suppose one sound = 200 and another 301. The interval is a fifth, slightly out of tune, as the higher should be 300. Coincident partials are 3d lower and 2d higher. $200 \times 3 = 600$; $301 \times 2 = 602$. $602 - 600 = 2$ = number of beats per second in this out-of-tune fifth.

Use of Beats. From what I have said, it becomes plain that the tuner will find beats very useful, and must devote himself to practicing the art of hearing them and counting them. For it is evident that if the number of beats between any two coincident partials is equal to the difference between the frequencies thereof, then if we calculate the exact required frequency of each of the two members of an interval and from this calculate the frequency of their lowest coincident partials, we can easily and at once take the difference between the two latter, and whatever the difference be, that number of beats per second will be heard between them when sounded together. Therefore if we tune the two members of the intervals so that we hear just that number of beats per second between them, we have tuned correctly. It then remains only to calculate these true values for the different notes of the piano

and thus to establish proper beat-rates everywhere.

There is really nothing unusual in all this for of course all tuners tune by counting beats, whether they call the process by this name or by another. The point I am making here is that this process is the proper and natural process and that is capable of being established mathematically.

We have now discussed to such an extent as is necessary for our present purposes the behavior of piano strings in vibration; and have discovered that this discussion, if properly understood, is found to give us all needed assistance in both tuning and voicing, provided we can calculate the necessary frequencies of the sounds required on the piano. We already know[1] that the piano does not permit pure tuning of the diatonic scale, but that a system of compromise must be adopted to accommodate the inequalities of the diatonic scale to the unyielding 12 keys of the piano's octave. The system of temperament is now so firmly ingrained in practice that it is, in fact, the real basis of all modern music; displacing the diatonic scale, which indeed is now little more than an artificial abstraction. Of this, however, I shall speak in the next chapter.

If the present chapter has seemed at all in-

[1] *Supra* Chap. I.

volved, this is only because I have had to treat an involved subject in simple language and small space. Still, all I have said here has been necessary and forms part of the argument which I am developing as to a system of piano tuning and tone-regulating; based on science and not on guesses or rule-of-thumb; and a good deal easier than if it were so based.

Chapter III

TEMPERAMENT

We have now reached the central position in the science of tuning. What has gone before has been enough to show that one cannot obtain a series of pure diatonic scales, in the quantity required for the performance of music, with a key-board comprising only twelve keys to the octave. The particular method adopted in Chapter I for the purpose of showing the truth of the assertion might of course be matched by a dozen others, without altering the facts in the least. For example, I might have pointed out that an ascending series of perfectly tuned perfect fifths, although nominally equal to seven octaves, yet actually exceeds them. I might have shown that three major thirds should be equal to an octave, if tuned pure one above the other; but that in fact they fall considerably short thereof. There are many other possible illustrations; but I have already shown, in the simplest manner, that some form of compromise is needed if pianos are to be tuned so as to make the performance of music in all tonalities tolerable despite the defective and inadequate 12-to-the-octave key-board.

The word "temperament" is generally used to indicate any one of the many such systems that have been, at one time or other, proposed and used. It must be remembered that the present type of key-board dates certainly from the fourteenth century and has scarcely undergone any change in details—positively none in essentials—during all that time.[1] This is an amazing commentary on the slowness of the human mind and its hatred of change. It is a fact that even the physical width of an octave of keys on the key-board has remained the same for certainly three hundred years. And the same slowness of development is seen in other details.[2]

Influence of the Key-board. The truth implied in Chapter I may now be realized completely: that the key-board has always exercised a distinctly enslaving influence upon the development of music. If we were not chained to the 12-note key-board by the tradition of music teaching and of instrument making, we should soon have a substitute, as easily taught to the hand, whereby at least the grosser imperfections of any temperament system might

[1] A terra-cotta model showing a rudimentary form of key-board used with an Hydraulikon or water-organ, has been found in the ruins of Carthage, and is assigned to the second century A. D. Cf. A. J. Hipkins' "Introduction to the Keyboard Instrument Collection," Metropolitan Museum of Art, New York.

[2] The great organ at Halberstadt, Germany, built in 1361 by the priest, Nicholas Faber, had a complete chromatic key-board, but with very wide keys. However, sixteenth century clavichords are preserved showing key-boards essentially identical with that of a modern piano in width and even in mounting.

be avoided. But to hope for this is to hope too much.

Meaning of Temperament. Actually, the word "temperament" means "tuning"; nothing else. Its derivations from the Italian and thence from the Latin, show this clearly. To "temper" sounds is to tune them. And this fact indicates that the necessity for a compromise from purity was recognised very early and that just intonation has never been even near accomplishment in ordinary practice. In fact the system of temperament now in use is probably the best that has yet been contrived, although it has one rival whose claims are not to be despised.

Equal Temperament. The twelve keys within the octave must, of course, represent amongst themselves the various degrees or steps of relationship existing within that interval. Seeing that we cannot gain purity of ratio with only twelve keys, it follows that we must divide up the octave in some way that will admit, as adequately as may be, of performing required music in a tolerable manner. Equal temperament is the name given to a system of dividing the octave into twelve equal parts. This being the case and the pitch proportion of the octave interval being 1:2, it follows that the proportion from semitone to semitone in equal temperament is $1:\sqrt[12]{2}$ or 1:1.0594631, cor-

rect to seven places of decimals. This ratio is the ratio of the equal tempered semitone, upon which the system is based.

The Equal Tempered Scale. This being so, we have only to select some standard of pitch for some one note and calculate up and down therefrom by the simple process of multiplying or dividing, semitone by semitone, by the factor 1.0594631.

The octave of course remains the one interval which retains its purity. This is so, because we must have a system of some sort, and the octave provides a foundation therefor. Hence the octave remains pure, and so if we once calculate the equal tempered pitch of the twelve semitones in one octave we can obtain that of any one of the notes situated in any other octave by multiplying by 2 for each octave of distance upwards or dividing by 2 for each octave of distance downwards.

Thus we may say that equal temperament is a system in which the octave interval is tuned pure and all other intervals are tuned in such a way as to produce a note-series of 12 equal parts within each octave.

Standard Pitch. The nominal standard now recognized for the basis of pitch in the United States is $A_{49} = 440$ v. p. s. at 68° Fahr. This pitch was adopted by the Music Industries Chamber of Commerce of the United States in 1925. Assuming this as our standard, we have the following

frequencies for the A throughout the compass of the piano, beginning at the lowest:

$$A_1 = 27.50$$
$$A_{13} = 55.00$$
$$A_{25} = 110.00$$
$$A_{37} = 220.00$$
$$A_{49} = 440.00$$
$$A_{61} = 880.00$$
$$A_{73} = 1760.00$$
$$A_{85} = 3520.00$$

The Piano Scale in Equal Temperament. With the above figures as our standard of measurement, and multiplying for each semitone upwards by the equal semitone ratio, we get the table on the next page, showing the complete range of frequencies for the entire 88 notes of the piano.

Object of the Table. In setting forth this table the object is not to confuse the student but to enable him to see how a system of tuning in equal temperament may easily be worked out; one far simpler and considerably more likely to lead to correct practice than any other based on guess. The table is the preliminary essential in the argument now to be set forth.

By examining the table we observe that if any column be taken, the figures from the top to bottom thereof represent that progression of frequencies in the sounds of an ascending octave. All

TABLE I. SHOWING FREQUENCIES (V. P. S.) OF ALL TONES ON THE PIANO, BASED ON THE 1925 STANDARD PITCH ($A_{49} = 440$) AND CORRECT TO TWO PLACES OF DECIMALS, IN EQUAL TEMPERAMENT

Name	C_4 Octave	C_{16} Octave	C_{28} Octave	C_{40} Octave	C_{52} Octave	C_{64} Octave	C_{76} Octave	C_{88} Octave
A	27.50	....	.....	.....	.....	.....	.....	.....
A♯—B♭	29.13	....	.....	.....	.....	.....	.....	.....
B♯—C♭	30.86	....	.....	.....	.....	.....	.....	.....
C	32.70	65.40	130.80	261.60	523.20	1046.40	2092.80	.....
C♯—D♭	34.64	69.28	138.56	277.12	554.24	1108.48	2216.96	.....
D	36.70	73.40	146.80	293.60	587.20	1174.40	2348.80	.....
D♯—E♭	38.89	77.78	155.56	311.12	622.24	1244.48	2488.96	.....
E —F♭	41.20	82.40	164.80	329.60	659.20	1318.40	2636.80	.....
F —E♯	43.65	87.30	174.60	349.20	698.40	1396.80	2793.60	.....
F♯—G♭	46.24	92.48	184.96	369.92	739.84	1479.68	2959.36	.....
G	48.99	97.98	195.96	391.92	783.84	1567.68	3135.36	.....
G♯—A♭	51.91	103.82	207.64	415.28	830.56	1661.12	3322.24	.....
A	55.00	110.00	220.00	440.00	880.00	1760.00	3520.00	.....
A♯—B♭	58.27	116.54	233.08	466.16	932.32	1864.64	3729.28	.....
B —C♭	61.73	123.46	246.92	493.84	987.68	1975.36	3950.72	.....
C	....	....	.....	.....	.....	.....	.....	4185.60

columns to right of any such column are ascending octaves and all columns to the left are descending octaves. From column to column we may proceed by either multiplying or dividing by 2 at each column. The octave interval is pure and the others are worked out on the equal semitone system as explained.

Comparison of Intonations. Before undertaking to show how tuning in equal temperament may most easily be performed, I shall give here a comparison, for the student's benefit, of three pure major diatonic scales built on two of the tempered notes taken from Table I.[1] The first scale is the tempered scale, the second is a pure diatonic major scale built on the same C = 261.6, the second is a pure major diatonic scale built on the tempered major second to C (D), and the third a pure diatonic major built on the tempered D flat. The pure diatonic scales are worked out from each on the basis of the ratios of the diatonic scale major (*supra* Chapter I); and the object of the comparison is simply to show what effect the equal temperament has on purity of intonation.

Advantages of Equal Temperament. These tables show clearly some of the peculiar defects of the equal temperament; but they show also

[1] The minor scale has not been considered because its difference from the major is merely in the detail of intervals. The arguments already made apply with equal force to the minor scale. See *supra*, Chapter I.

some of its peculiar advantages. For it will be seen that at the cost of some perceptible dissonances in certain intervals—dissonances which we shall shortly calculate definitely—we gain the ability to perform music in all tonalities, by aid of the traditional 12-note key-board.

TABLE II. COMPARATIVE FREQUENCIES OF EQUAL TEMPERED SCALE AND THREE DIATONIC MAJOR SCALES TAKEN ON THE 1ST, 2ND, AND 3RD DEGREES OF THE EQUAL TEMPERED SCALE

Equal Tempered C Scale (Chromatic)	Pure Diatonic C Scale (Major)	Pure Diatonic D Scale (Major)	Pure Diatonic Db Scale (Major)
C_{40} 261.6	C 261.6	.....	.....
C♯—Db_{41} ...277.1	.....	D 293.6	Db 277.1
D_{40} 293.6	D 294.3	.....	.....
D♯—Eb_{43} ...311.1	.....	E 330.25	Eb 311.7
E_{44} 329.6	E 327.0	.....	.....
F_{45} 349.2	F 348.8	F♯ 367.00	F 346.3
F♯—Gb_{46} ...369.9	.....	G 391.46	Gb 369.4
G_{47} 391.9	G 392.4	.....	.....
G♯—Ab_{48} ...415.3	.....	A 440.4	Ab 415.6
A_{49} 440.0	A 436.0	.....	.....
A♯—Bb_{50} ...466.1	.....	B 489.3	Bb 461.8
B_{51} 493.8	B 490.5	.....	.....
C_{52} 523.2	C 523.2	.....	C 519.5
C♯—Db_{53} ...554.2	.....	C♯ 550.5	Db 554.2
D_{54} 587.2	.....	D 587.2	.....

Disadvantages of Equal Temperament. At the same time we must not lose sight of the fact that in reality the equal temperament is a compromise, and a loose compromise, with fact. If it were not for the organ and piano, the imperfections of equal temperament would be more easily perceived; but the dynamic powers and immense harmonic resources of these last two instruments have endeared them to musicians and have concealed the roughness of their intonation. No one who has

read the previous chapter and understands how to listen for beats, however, can long tolerate the intonation of the organ on such intervals as minor thirds. The sustained sounds of that instrument bring out the beats very clearly and produce a generally distressing effect for delicate ears. Of course, the truth is that most of us are so used to tempered intonation that we recognize nothing else and know of no other possibility. Yet the fact remains that whoever has heard one of the few experimental key-board instruments that have been constructed to play in pure intonation has been entranced with the sweetness of music thus played. It is far more beautiful than tempered intonation and, in fact, seems to impart to the music of these instruments a new graciousness and concord.

So long, of course, as the manufacture of pianos and organs is stressed rather on its industrial than on its artistic side we shall probably have to remain content with equal temperament. But it might as well be observed that if the piano and organ were out of the way, music throughout the world would be on some other basis of tuning than equal temperament within ten years.[1]

Meanwhile we must be content to tune in equal temperament as well as we can, knowing that when

[1] Cf. Helmholtz, 3rd edition, Appendix 20, by A. J. Ellis. Perronet Thompson, "Theory and Practice of Just Intonation." Zahm, "Sound and Music." Redfield, "Music, a Science and an Art."

such work is well done it is very satisfactory, and serves well the requirements of modern music and modern musicians.

Meantone Temperament. Before going on to consider the method of tuning in equal temperament, however, I should like to mention the immediate predecessor of the equal temperament; the famous meantone temperament, which flourished from the sixteenth to the early part of the nineteenth century and may be occasionally found today on organs in obscure European villages. This system consists in tuning a circle of fifths equally flat, in such a way as to leave all the thirds major nearly pure. Before, however, this system can be used for all required tonalities, it is necessary to have extra key-levers, for the flats and sharps of adjacent notes are not all identical. For the best performance in all tonalities, not less than 27 tones to the octave are required, but the greater number of tonalities can be used with 16 keys to the octave; the additional keys being for D flat, E flat, A flat, and B flat. The ordinary 12-note key-board would give, of course, starting from C, only the circle of fifths, which when transposed to the same octave result in the following scale:

C, C♯, D, D♯, E, F, F♯, G, G♯, A, A♯, B.

Unfortunately, in this temperament, C♯ will not do for D♭, D♯ for E♭, G♯ for A♭ or A♯ for B♭.

These notes of course have to be incorporated somehow and in some eighteenth century organs were built into the manual by dividing up some of the black keys, which were cut across the middle with the back half slightly raised above the front. The meantone system gives a "sweet" and harmonious effect for nearly all tonalities when used with 16 tones to the octave, although of course this number still lacks 11 tones to make it quite adequate. However, even with 12 tones to the octave, an experiment in meantone temperament can be tried, and will sound very attractive so long as one keeps within the range of tonalities available. To make the best of the key-board we have, the following method may be tried. Start with C and tune the major third C—E perfect. Then tune the fifths from C round to E by fifths and octaves, equally flat, testing until the right degree of flatness is obtained. All other notes can be had by tuning pure major thirds and pure octaves. With this tuning it is possible to play in the keys of B flat, F, C, D and A major, and G, D, and A minor. The reason, of course, is as stated above. This is a very useful experiment and if tried carefully will enable the student to play old music in the tuning for which it was intended; an experience sometimes most illuminating and delightful.[1]

[1] The student might consult the extremely useful and interesting article "Temperament," by James Lecky, in Grove's "Dictionary of Music and Musicians."

The "Beat" System. I have mentioned these things because I am anxious to have the student understand that the equal temperament is not the only possible system of tuning. But to get now definitely to the method of tuning in equal temperament, which is the system which the tuner today uses universally, let us see what is the nature of our problem.

The table of frequencies (Table I) suggests the method we shall use. We know[1] that beats afford us a simple and accurate way of judging the deviation from consonance of one sound sounded with another. Since we cannot trust the unaided ear to tune successively a series of equal tempered semitones, we make use of the method of comparing one sound with another. Thus we have only to ascertain the number of beats that are produced by the members of various intervals in equal temperament, beating against each other, and then to tune these intervals by counting their beats.

Beats arise between coincident partials and therefore if we lay out a series of intervals from some given standard and calculate the coincident partials in each, we can by subtraction find out how many beats are heard when that interval is rightly tempered.[2]

I have found it is easiest to tune by octaves,

[1] *Supra,* Chapter II.

[2] Compare Chapter II, "Coincident Partials," to find what partials coincide in any interval.

fifths and fourths; by fifths and fourths for the octave of tones, usually F_{33}—F_{45}, chosen for the "bearings" or foundation work and by octaves up and down thereafter. The other intervals involved may then be used for testing the correctness of the work as it proceeds. Such testing is best done by means of major and minor thirds and major and minor sixths, whose rates of beating in equal temperament the tuner must therefore know.

Beats in Equal Tempered Intervals. The following table (Table III) gives the number of beats per second in the ascending minor thirds, major thirds, fourths, fifths, minor sixths and major sixths from each degree of the equal tempered scale between C_{28} and C_{52} inclusive, correct within one place of decimals. Since, however, the tuner will find his powers extended to the utmost in estimating the beat-rates of fourths and fifths at the figures given, and with this relatively large error, it has been thought better to adopt this course. For suggestions as to counting beats and other practical matters of the same sort the following chapters should be consulted.[1]

[1] The first table of beats calculated in this manner, for use in tuning, was set forth by J. C. Miller, of Lincoln, Neb., U. S. A., an eminent exponent of the art, whose unselfish labors for the benefit of his fellows can never be too much admired. Calculated correct to six places of decimals and with some supplementary matter, the Miller tables were published in *The Tuner's Magazine* (Cincinnati), for December, 1914. A less elaborate edition was published correct to two places of decimals in the *Music Trade Review* (New York) during 1911, and in the London *Music Trades Review* (London), 1914. The adoption of the 440 pitch in 1925 has necessitated a recalculation of the beat rates, but the changes in the figures are trifling.

TABLE III. APPROXIMATE NUMBER OF BEATS PER SECOND IN INCLUDING INTERVALS BETWEEN C_{28} AND C_{52}, EQUAL TEMPERAMENT

Note	Frequency	Minor Third	Major Third	Perfect Fourth	Perfect Fifth	Minor Sixth	Major Sixth
Pitch Ratio		5:6	4:5	3:4	2:3	5:8	3:5
Coinciding Partials		6:5	5:4	4:3	3:2	8:5	5:3
C_{28}	130.8	7.0	5.0	0.6	0.4	8.4	6.0
C♯—Db_{29}	138.5	7.0	6.0	0.6	0.4	8.0	6.5
D_{30}	146.8	8.0	6.0	0.7	0.4	9.4	6.7
D♯—Eb_{31}	155.5	8.5	6.0	0.8	0.5	9.5	7.3
E_{32}	164.8	9.0	6.0	0.8	0.6	10.4	7.3
F_{33}	174.6	9.0	7.0	0.8	0.6	11.3	7.8
F♯—Gb_{34}	184.9	9.0	7.5	1.0	0.6	11.2	8.8
G_{35}	195.9	10.0	8.0	1.0	0.7	11.7	9.3
G♯—Ab_{36}	207.6	11.0	8.0	1.0	0.7	12.8	9.6
A_{37}	220.0	12.0	8.0	1.0	0.8	14.0	9.7
A♯—Bb_{38}	233.0	12.5	9.0	1.0	0.9	14.5	10.7
B_{39}	246.9	13.0	10.0	1.0	0.9	15.7	11.4
C_{40}	261.6	14.0	10.0	1.0	0.9	16.3	12.0
C♯—Db_{41}	277.1	15.0	11.0	1.0	0.8	16.8	12.8
D_{42}	293.6	16.0	12.0	1.0	0.8	18.3	13.4
D♯—Eb_{43}	311.1	17.0	12.0	1.5	1.0	19.8	14.1
E_{44}	329.6	18.0	13.0	1.6	1.1	20.8	...
F_{45}	349.2	19.0	14.0	1.7	1.2	...	...
F♯—Gb_{46}	369.9	19.0	15.0	1.8	...	...	...
G_{47}	391.9	21.0	16.0	2.0	...	...	...
G♯—Ab_{48}	415.3	23.0	16.0	...	...	...	...
A_{49}	440.0	24.0	...	...	...	...	...
A♯—Bb_{50}	466.1	...	...	...	...	...	...
B_{51}	493.8	...	...	...	...	...	...
C_{52}	523.2	...	...	...	...	...	...

Note: The beat-rates are correct only to 1 place of decimals. Greater accuracy is merely a matter of calculation, of course.

Use of the Table. I do not propose that the tuner shall try to count accurately the beats per second enumerated above; at least immediately. But the special use of the table is to provide a model which will indicate closely enough the exact amount of impurity in each interval as required for equal temperament. This impurity is measured by the beat-rate, instead of by first showing what the ratios of impurity should be and then proposing a rough approximation thereto to be measured by tuning "about so flat" or "about so sharp." By giving definite beat-rates I make it possible, as the next chapter will show, to tune with unusual accuracy after a reasonable amount of practice.

The immediate point is that the tuner should know how many beats per second each interval in the equal temperament scheme really involves, at standard pitch. Knowing this he knows what he ought to do; and if he can learn what he ought to do, then he can the sooner learn how nearly to attain in practice to that ideal.

Wide and Narrow Intervals. It only remains to note which intervals are to be widened and which narrowed in equal temperament tuning. The facts are simple and easily understood. They may be stated as follows:

An ascending series of twelve fifths nominally coincides with an ascending series of seven octaves

from the same notes. Actually the fifth series comes out wider than the octaves, in the ratio 531441 : 524288. Hence equal tempered fifths must be narrowed; the amount of squeezing in each case being determined for the tuner by counting the beats set forth in Table III.

An ascending series of twelve fourths nominally coincides with an ascending series of five octaves from the same note. Actually the fourth series comes out narrower than the octaves in the ratio 144 : 192. Hence equal tempered fourths must be widened, the amount in each case being determined for the tuner by counting the beats.

Although we are here working by fourths and fifths mainly, it is necessary to understand also the characteristics of the other intervals. Thus:

Three ascending major thirds nominally coincide with an octave but actually are short in the ratio 125 : 128. Hence the major thirds must be widened in equal temperament, the amount thereof in each case being determined as in Table III.

Four ascending minor thirds nominally coincide with one octave but actually exceed it in the ratio 1296 : 1250. Therefore they must be narrowed in each case, the amount thereof being determined for the tuner by counting the beats as set forth in Table III.

In the same way we find that in equal tempera-

ment the major sixths are all wide and the minor sixths narrow.

Increase in Beat-rate. In the nature of the case, the beats taking their origin from coincident partials, and the ratio of pitch from octave to octave being 1:2, it follows that the number of beats in any interval doubles at each octave ascending and halves at each octave descending. By suitable multiplications and divisions therefore, the beat-rate in any interval in any octave of the piano may be obtained from Table III. It is worth while pausing here to note that the higher octaves comprise intervals in which the beats are very rapid and conversely the lower octaves have very slow-beating intervals. Thus the ascending fifth F—C beats as follows, from the lowest C upwards:

	v. p. s.	
F_{9}....C_{16}	.15	or a little more than 1 in 7 seconds.
F_{21}....C_{28}	.30	or 3 times in 10 seconds.
F_{33}....C_{40}	.60	or 6 times in 10 seconds.
F_{45}....C_{52}	1.20	or 12 times in 10 seconds.
F_{57}....C_{64}	2.40	or nearly 5 times in 2 seconds (24 in 10 seconds).
F_{69}....C_{76}	4.80	or nearly 5 times per second (48 in 10 seconds).
F_{81}....C_{88}	9.60	or nearly 10 times per second (96 in 10 seconds).

The Fourths and Fifths Circle. My preferred method of tuning is by a circle of fourths and fifths. By the method noted on pp. 94 and 95, fourths and fifths are alternated in such a way that after the first descending fifth has been tuned,

every note to be tuned is flatted, whether it belongs to a fourth or fifth. This is made possible by taking all the fourths descending and all the fifths ascending, whereby fourths can be expanded and fifths contracted in a continuous process of flatting each note in turn; as will at once be seen by glancing at the table mentioned above.

Practical suggestions for tuning this circle according to the beat-rate system will be found in the next chapter. The notes are taken in the octave F_{33}—F_{45}, around C_{40}, and the remainder are tuned by octaves up and down. The circle is known among tuners as "the bearings."

A Note on the Scientific Method. This concludes all that it is necessary to say about the acoustical foundation of the system universally employed throughout the Occident for the tuning of musical instruments. The practical side of the art is treated in the following chapter. I should not wish to conclude the present remarks, however, without pointing out that I have treated the subject fully but not necessarily obscurely. In point of fact one cannot explain the rationale of equal temperament without going into considerable detail. If the reader is content to do without the explanations, and to accept Table III together with the following chapter at their face value, he may skip all that I have set forth in previous pages and take my conclusions as stated. But if he chooses any

rapid road like this he will find that rapid roads are often slippery, and he will miss the satisfaction which comes from knowing why as well as how.

There is actually nothing difficult in the method adopted here; and the practical tuner may be assured that the system of counting beats set forth in this and following chapters is not only quite practical but on the whole easier than any other with which I am at present acquainted, and which comes within the limited range of practical possibility. As for accuracy, there is no comparison between this and any system founded on less exact reasoning.

A Note on Intonations. I should feel, too, that this book has fulfilled one of its objects if it induces some students to take up the study of intonation in general, by which I mean the general problem of expressing musical scales in practical form. The equal temperament is a good servant but a bad master; and although the practical piano tuner must, in present conditions, use it as it stands, he cannot divest himself of a certain amount of responsibility in the matter of its general approval. For after all, tuners could do something to prepare the world for a better system if they wished to; and if they knew that improvement is actually possible. What we need is to realize that the equal temperament is a purely artificial system resting

upon a consent gained rather on account of the absolute necessity for the piano having it, than for any fundamental musical reason. To get something better we need a method which will either (1) allow more strings to the octave or (2) give us a mechanism capable of making instant changes as required in the pitch of given strings, so that modulation may be as facile as it is now.[1]

Let it be understood, however, that just intonation is an ideal to be striven for; and that tuners should by all means make it their business to acquaint themselves with the beauty and sweetness of pure intervals, if only to remind themselves that these really exist.

The scope of the present volume does not permit me to go into detail as to experimental instruments that have been made to give just or nearly just intonation, but I wish that every reader would take the trouble to consult the admirable discussion of this most interesting subject to be found in Ellis' 20th Appendix to the 3rd English edition of Helmholtz.[2] At the end of this book I have given a short list of books which the student who is desirous of pursuing his acoustical and musical studies further, may consult to his advantage.

[1] One such system was worked (by Dr. Hagaman, of Cincinnati) twenty-five years ago, and one may hope that it may yet be heard of in some commercial practicable form.

[2] John Redfield in his "Music, a Science and an Art" (1927) has discussed the temperament question with vivacity and force.

Chapter IV

PRACTICAL TUNING IN EQUAL TEMPERAMENT

In the light of the discussion that has gone before, let us now see how we may put our ideas into practice. It is plain from what has been already said that equal temperament is a perfectly simple system admirably adapted to modern ideas and methods in musical composition and in the making of musical instruments. Until there shall come that change in public taste which demands something finer, we shall have tempered pianos, tempered orchestras and tempered intonation generally; with our ears more and more becoming used to tempered sounds, and unused to pure sounds. It is therefore highly important not only that the tuner should be thoroughly capable of doing the very best work in temperament that can be done, but also that he should make it his business to realize every day and every hour that the work he is doing involves in reality a compromise with truth; necessary no doubt, but a compromise just the same; and one which exists solely because instruments, musicians, and the public alike are unready for anything better.

Recognizing Just Sounds. In the circumstances

and considering the inherent difficulty of tempering accurately by estimation of ear, I most earnestly advise every student to practice the tuning of pure fifths, fourths, and thirds. Unisons and octaves must be tuned pure anyhow, but most tuners, in common with virtually everybody else, are familiar only with the tempered forms of the other intervals and never dream of asking how they sound when purely intoned. But in order to recognize with any sort of accuracy the number of beats per second that a tempered interval is generating, it is absolutely essential that one should be acquainted with the true condition of that interval; familiar with its sound when evoked in purity. Thus I would counsel every reader of this book to form the habit of always tuning all intervals pure and hearing them satisfactorily as such, before attempting to temper them; and also to get into the equally valuable habit of tuning, for his own amusement and satisfaction, series of pure chords on the piano; which of course can be done so as to be satisfactory for one tonality, and even to that extent playable.

Measure of Purity. The measure of purity is the absence of beats. If intervals whose ratios of frequency are such as to avoid alteration in phase relations[1] are tuned on any instrument with absolute accuracy, there will be no beats between them.

[1] See *Supra*, Chapter II.

I omit reference to the "beat-tones," otherwise known as resultant or combinational tones, which are in reality generated by very rapidly moving beats from high coincident partials in intervals that otherwise would have no beats; but these beat-tones are true musical sounds and for the tuner's purpose need not be considered in the present discussion; especially as they are almost imperceptible on the piano.[1] The fact, then, that no beats are heard is a test quite accurate; and the work of tuning is immensely facilitated if the tuner is able to determine for himself the existence of a condition of beatlessness, instead of always being vague on this point.

Unison Tuning. The acquirement of a cultivated ear for purity of interval cannot better be begun than by learning to tune unisons correctly. Considering also that tuning of unisons comprises about two-thirds of the work of tuning a piano, since most of the strings are triply, and nearly all the rest doubly, strung, it will be seen that this important part of the tuner's work deserves the most careful attention. It is fortunate that the unison is the simplest of intervals to comprehend and to appreciate aurally. It is requisite in beginning

[1] Tuners whose ears have attained a sufficient degree of delicacy, and who are scientific enough to wish to go into the matter, may consult Zahm, "Sound and Music," Tyndall, "On Sound," Helmholtz, "Sensations of Tone." Beat-tones, as described best perhaps by Koenig (quoted in Zahm), do of course afford a test of the absolute purity of an interval.

the study of tuning to ascertain with complete certainty the peculiarities of beats. Two tuning forks tuned in unison and with one then slightly loaded with a minute piece of wax, or other material, afford a simple and easy experiment in beat production.[1] It will be useful to begin by making such an experiment, listening carefully to the beats until the peculiar alternate rise and fall of the sounds is so plain that it can never again be mistaken. The opposite experiment, made by removing the load and returning the forks to complete unison, presents the case of a perfect unison, with complete absence of beats. Tuning fork vibrations, by the way, are interesting as providing an almost perfect form of simple fundamental sound free from partials.

To tune two piano strings in unison is not a very difficult task if it be gone about rightly. In the first place, it is well to listen carefully to the work of a professional tuner, when the opportunity occurs, with the object of noting by ear how he adjusts his unisons. A little practice will enable one to hear instantly the difference between the beating sound of two strings which are out of tune with each other and the pure continuous beatless sensation of sound developed when the unison is perfected. Having once obtained some facility in thus cultivating the hearing, the student may

[1] Cf. Chapter II.

obtain a tuning hammer and attempt to do some practical adjustment of unisons for himself.

Argument concerning the manipulation of the hammer would at this stage be out of place, I feel, for it would tend rather to confuse than to assist the student.[1] Let me then simply say that the tuning hammer is to be placed on a tuning-pin corresponding with one string of a triple unison. Let one string of the triple unison be damped off, leaving two to sound when the piano key is struck. If the piano has not been tuned recently the student will undoubtedly hear beats; and if these are not distinct or frequent enough, let the tension on the string be relaxed by turning the pin slightly toward the left or bass end of the piano. Now, let the reverse operation be undertaken, and the hammer turned back towards the operator, thus gradually tightening up the string again. As this is done it will be observed, if the key is repeatedly struck, that the beats, which at first we may suppose to have been quite frequent, become slower and slower, until when the string has been rightly tuned, they disappear altogether, leaving a pure continuous uninterrupted sound.

Practice. In beginning the work of learning to tune pianos, it is advisable to practice for some time in bursts of from fifteen to thirty minutes each, on simple adjustment of unisons. The ma-

[1] See the next chapter.

nipulation of the hammer, of which I speak at length in the next chapter, now, of course, begins to claim attention; but for the present it is enough to say that the pin must be turned without wrenching its outer end and without twisting or "springing" it. In working on upright pianos the beginner will be well advised to rest his arm and keep the handle of the tuning hammer nearly vertical.

It will next be proper to undertake setting the unisons of an entire piano. Not until this has been accomplished is the student fit to take the next step. It will be observed that whereas the middle strings afford a comparatively simple task, those of very low and very high frequencies alike are more and more elusive; and careful practice and listening are required before they can be mastered. The measure of purity, be it remembered, is absence of beats; and so long as beats can be heard the unison is not pure.

Octave Tuning. The octave is the unison transposed. Hence octave tuning is just as simple as unison tuning, in principle, and almost the same in detail. The beats arising in a two-string unison are between the fundamentals of two sounds, while in an octave the beats are between the 1st partial of the higher and the 2nd of the lower; the octave proportion being 1:2 and the coincident partials therefore being Nos. 2 and 1 respectively.[1] Thus

[1] Cf. Chapter II, p. 58.

throughout the entire middle portion of the piano anyhow, there will be very little difficulty in tuning octaves, once the student has learned to adjust the unisons accurately, for exactly the same beats are heard and the same blending of the beats into a condition of beatlessness as the octave is perfected, until a perfect octave is almost as complete a blend of sound as is an unison.

Exact Tests. In certain regions of the piano it is quite impossible to obtain certainty of octave tuning merely by estimating the extinction of beats between the two members of the interval. In the low bass particularly, the coarseness of the strings and the almost inevitable impurity of their intonation lead to the generation of all kinds of false beats, which confuse the student and are a source of annoyance and inaccuracy even to the expert. The student should of course practice tuning octaves throughout the entire compass, but he will find that in the low bass he must have some test for accuracy better than afforded by aural comparison of the two members of the interval. Fortunately, other tests are available, and each is capable of giving highly correct results.

The octave comprises a fourth and a fifth in succession. A fourth above C_{28} runs to F_{33} and a fifth from that runs from F_{33} to C_{40}. If now, whilst tuning the octave C_{28}—C_{40} (say) we sound the fourth C_{28}—F_{33} and then the fifth F_{33}—C_{40}, and

find the beats in the fourth equal in number to the beats in the fifth, the octave has been tuned accurately. This is so because all fourths and fifths in equal temperament are distorted slightly so that the coincident partials are actually a little distorted also. In the present case, the coincident partial is C_{52}, the 4th partial of C_{28}, the 3rd of F_{33}, and the 2nd of C_{40}.

The first octave test therefore is made by ascertaining the number of beats between the fourth above the lower sound and comparing these with the beats in the fifth below the upper sound. If the beats are the same in number, then the octave is perfect. But, if the test is made between lower fifth and upper fourth, the upper fourth will be found to beat twice as fast as the lower fifth, as may be seen from the above explanation.

Minor Third and Major Sixth. For the lower regions of the piano especially, but useful everywhere, is the test of the ascending minor third and descending major sixth. If we are tuning, for instance, from C_{28} to C_{40} we try the minor third C_{28}—$E\flat_{31}$ and note its beat-rate. Then we try the major sixth $E\flat_{31}$—C_{40} and try its beats. If the beats in the two cases are equal in rate, then the octave is tuned accurately. It will be observed that this is the same idea set forth in the previous paragraph. The $E\flat$ is the common element, and the minor

third and major sixth are complementary. The coincident partial is the 6th of C_{28}, the 5th of $E\flat_{31}$, and the 3rd of C_{40}. But if the sixth be the lower and the third the upper, complementary intervals used, the third will in this case, of course, beat twice as fast as the sixth.

Beat-rates in Thirds and Sixths. It is well to note in passing that as shown in the tables in Chapter III (*supra*), the beats in thirds and sixths, major and minor, are considerably faster than in fourths and fifths; and the student after tuning an octave may profitably examine the complementary thirds and sixths within that interval for the purpose of studying their beat-rates.

The Tenth Test. A tenth is an octave plus a major third. A good octave test is to be found here also by using the major under-third and tenth. In tuning C_{28} to C_{40}, we may test by the major under-third C_{28}—$A\flat_{24}$, as compared with the tenth $A\flat_{25}$—C_{40}. The coincident partial is the 5th of $A\flat_{25}$, the 4th of C_{28} and the 2nd of C_{40}. This test is useful throughout the entire compass and especially in the lower registers.

Observe that beat-rates, as shown by Table III (Chapter III), vary as the frequencies of their generators, so that the nearer we approach the lower bass, the slower are all the beat-rates. In fact, the respective beats of the fourths and fifths cannot be distinguished at all in the lower bass,

and we have to depend on thirds and sixths. It is very important, of course, to know how many beats in a second any given interval should have; and Table III supplies this requisite.

Counting Beats. The tuner, for practical purposes, must count his beats by mere aural estimation. The result is never perfectly accurate. It is, however, the only method that can be used in practical work, and the method, therefore, that we must develop to the highest possible degree of excellence. In the first place it will be noted that Table III (Chapter III) gives the beat-rates accurate only to within 0.5 of a beat per second. This is simply because, although the error is mathematically large, the human ear, at least with the evanescent tones of the piano, cannot judge any more delicately, and even then needs practice and patience. It will usually be found that for accurate work beat-rates of from 2 to 5 per second are most easily counted. Above this is difficult; below is equally so. Beats slower than 1 per second are hard to hear. However, the tuner may accustom himself to estimating beat-rates by one or two simple methods.

Seconds' Watch. Watches are usually provided with seconds' hands and these usually make four ticks per second. By listening carefully for say ten minutes at a time, the student can soon learn to hear accurately the equivalent of a beat-rate of

4 per second. But the precise tick-rate of one's own watch must be accurately determined.

Pendulum Clock. Pendulum clocks of the large sort often have very slow swinging pendulums. The best ones always beat seconds, 60 beats to the minute.

Pendulum. Ellis suggests (App. 20 to Helmholtz), that the student may make himself a pendulum from a piece of string and a curtain ring, with provision for shortening or lengthening the string readily. Now, for counting during any length of time, as for instance 5 seconds, which is a useful unit of time in counting beats on the piano, we may arrange the length of the string as shown below:

Length of string from beginning of vibrating portion to middle of ring in inches:	*Complete vibrations (to and fro)*	
	in 10 seconds	*in 5 seconds*
9.875	10	5
4.375	15	7.5
27.1875	6	3

It is important to note the manner of measuring, as above.

These three beat rates are very important, especially the first and third, in the practical work of tuning.

Other methods may suggest themselves to the student. The perforated rotating disk to be found in every high school physical laboratory can be used also to give series of taps (by holding a card

against a circle of the perforations while the disk is rotated), of any required speed.[1]

Of course the point is that the tuner ought not to trust to guess work, but should try to *know* when he hears beats, what their rate really is. He can learn to do this; and learn easily. By watching and counting the swings of a pendulum such as that described above he can soon learn to feel the rate of swing; which is an exceedingly valuable accomplishment and one easy to acquire. Certainly, it is impossible without some such training ever really to do distinguished work in the most important and most difficult branch of tuning pianos; that which is called "laying the bearings," and which we must now consider.

Laying the Bearings. The scheme already laid out (Chapter III, *supra*), for tuning the central octave space on the piano in fourths and fifths forms the basis of the explanations now to be made. Reproducing this in type and appending the beat-rate as ascertained for each interval from Table III and the frequency as given in Table I, we get Table IV, pages 94 and 95.

[1] The Metronome may be used for the same purpose, as follows. The required beat-rate is expressed in beats per minute and then multiplied by 2. The Metronome is then set at the resulting figure and set going. If now every alternate tick be counted the resulting rate will be equal to the number of beats per second. Thus: 3 beats in 5 seconds $= 3 \times 12 = 36$ beats in $5 \times 12 = 60$ seconds $= 1$ minute. $36 \times 2 = 72$ beats per minute $= 6$ beats in 5 seconds. Counting alternate ticks, as by setting the bell to ring at every other tick, we get 3 rings in 5 seconds, and so on.

TABLE IV. SCHEME OF "LAYING THE BEARINGS" IN EQUAL TEMPERAMENT BETWEEN F_{33} AND F_{45} BY FOURTHS AND FIFTHS, WITH TESTS

NOTE 1.—5ths must be contracted and 4ths expanded. But by taking all 5ths up and all 4ths down, each succeeding note to be tuned is *flatted;* thereby simplifying matters. The first F, however, is a 5th *down,* and this F (and it alone) is *sharped.*

NOTE 2.—The pitch is the 1925 (U. S. A.) Standard $A_{49} = 440$.

NOTE 3.—5ths, minor 3rds, minor 6ths, are contracted. 4ths, major 3rds, major 6ths, are expanded.

NOTE 4.—The figures of beat-rates are correct only to one place of decimals.

Step	Notes	Interval or Test Chord	Frequencies	Beats per Second	Beats in 10 Seconds	Beats in 5 Seconds
1	C_{52}—C_{40}	Octave	523.2—261.6	0.0	0.0	0.0
2	C_{40}—F_{33}	perfect fifth	261.6—174.6	0.6	6.0	3.0
3	C_{40}—G_{35}	perfect fourth	261.6—195.9	1.0	10.0	5.0
4	G_{35}—D_{42}	perfect fifth	195.9—293.6	0.7	7.0	3.5
5	F_{33}—D_{42}	major sixth	174.6—293.6	7.8	78.0	39.0
6	D_{42}—A_{37}	perfect fourth	293.6—220.0	1.0	10.0	5.0
7	F_{33}—A_{37}—C_{40}	major triad	.....	...	....	...
8	F_{33}—A_{37}	major third	174.6—220.0	7.0	70.0	35.0
9	A_{37}—E_{44}	perfect fifth	220.0—329.6	0.8	8.0	4.0
10	A_{37}—C_{40}—E_{44}	minor triad	.....	...	....	...
11	C_{40}—E_{44}	major third	261.6—329.6	10.0	100.0	50.0
12	G_{35}—E_{44}	major sixth	195.9—329.6	9.3	93.0	46.5
13	E_{44}—B_{39}	perfect fourth	329.6—246.9	1.0	10.0	5.0
14	G_{35}—B_{39}—D_{42}	major triad	.....	...	....	...
15	G_{35}—B_{39}	major third	195.9—246.9	8.0	80.0	40.0
16	B_{39}—$F\#_{34}$	perfect fourth	246.9—184.9	1.0	10.0	5.0
17	$F\#_{34}$—A_{37}—D_{42}	inverted major triad	.....	...	....	...
18	$F\#_{34}$—A_{37}	minor third	184.9—220.0	9.0	90.0	45.0
19	$F\#_{34}$—$C\#_{41}$	perfect fifth	184.9—277.1	0.6	12.0	3.0

Step	Notes	Interval or Test Chord	Frequencies	Beats per Second	Beats in 10 Seconds	Beats in 5 Seconds
20	$F\#_{34}$—A_{37}—$C\#_{41}$	minor triad	.....	...	....	...
21	A_{37}—$C\#_{41}$—E_{44}	major triad	.....	...	....	...
22	A_{37}—$C\#_{41}$	major third	220.0—277.1	8.0	80.0	40.0
23	$C\#_{41}$—$G\#_{36}$	perfect fourth	277.1—207.6	1.0	10.0	5.0
24	$G\#_{36}$—B_{39}—E_{44}	inverted major triad	.....	...	....	...
25	$G\#_{36}$—C_{40}	major third	207.6—261.6	8.0	80.0	40.0
26	$G\#_{36}$—$D\#_{43}$	perfect fifth	207.6—311.1	0.7	7.0	3.5
27	$F\#_{34}$—B_{39}—$D\#_{43}$	major triad	.....	...	....	...
28	$F\#_{34}$—$D\#_{43}$	major sixth	184.9—311.1	8.8	88.0	44.0
29	B_{39}—$D\#_{43}$	major third	246.9—311.1	10.0	100.0	50.0
30	$D\#_{43}$—$A\#_{38}$	perfect fourth	311.1—233.0	1.5	15.0	7.5
31	F_{38}—$A\#_{38}$—D_{42}	inverted minor triad	.....	...	....	...
32	$F\#_{34}$—$A\#_{38}$	major third	184.9—233.0	7.5	75.0	37.5
33	$A\#_{38}$—D_{42}	major third	233.0—293.6	9.0	90.0	45.0
34	$A\#_{38}$—F_{45}	perfect fifth	233.0—349.2	0.9	9.0	4.5
35	$C\#_{41}$—F_{45}	major third	277.1—349.2	11.0	110.0	55.0
36	F_{38}—F_{45}	Octave	174.6—349.2	0.0	0.0	0.0

There are two observations to be made immediately. The first is that although Table IV shows 36 steps, only 13 notes are actually tuned, and the remaining steps represent tests made with intervals and chords generated during the progress of the tuning. These test intervals and chords are of the utmost importance, just as important as any other element of the work, for they afford a complete measure of the correctness of the tuner's progress. But the actual tuning is confined to the series of fourths and fifths shown.

The second is that to count beats at something very close to these rates is not impossible by any means. I counsel the student to realize that any definite method like this has the inestimable advantage of being founded on fact. What is more to the point, such a method leads to that much closer accuracy which should distinguish masters of the art.

Variations in Pitch for Practical Tuning. The figures given are sufficiently accurate for any pitch between C 261.6 and C 264, which range covers the common variations as found in modern pianos. In strict fact, any rise in pitch above the 1925 (U. S. A.) standard of $C_{40} = 261.6$ v. p. s. involves progressive rise in beat-rate. But the amount of increase is usually too small to be considered for practical purposes.

Importance of Accuracy. Of course I cannot

too strongly urge the importance of accuracy, of not being content to do things fairly well or even reasonably well; but of insisting to the utmost upon the possibility of doing ever and ever more accurate, more scientific, and more complete, work. Tables III and IV probably represent the utmost attainable in practical accuracy, and the beat-rates given in these tables can be obtained by those who will practice the art of tuning with patient devotion. The artist will obtain them, given a good piano for his field of operations.

Methods of Using Tests. The test thirds and sixths, and the test triads are to be used constantly throughout the work. Observe carefully the rise in beat-rate of the ascending thirds and sixths. This rise must be accurately measured. It will be found, of course, that the beat-rate doubles in each octave, and the extreme thirds should show this progress. No better test of the accuracy of the bearings can be found. It is not sufficient to "come out right," by which is meant, to arrive at the last step and find the final octave reasonably clear. It is necessary that every step should be right. This means care, patience, study; which lead to mastery.

Tuning from the "Bearings." From the "bearings" the tuning proceeds by octaves and unisons according to the methods laid down and explained in the earlier part of this chapter. The student is

again warned to see that his octave tuning does not begin to deviate from accuracy by the accumulation of imperceptible into intolerable errors; and to this end the constant use of the various tests already explained, as well as of double octaves and triads, is recommended.

Obtaining Required Temperament in Intervals. Lastly, let me say again that the only way to tune intervals, so that their beat-rates shall be reasonably accurate, is first to tune them pure and then to make the necessary corrections up or down. It is impossible in any other way to acquire true delicacy of ear. No other method will produce the required results. This is an immensely important truth, which covers one of the most neglected elements in the art. The rule of tuning all intervals pure before proceeding to temper, is essential; and the student ought early to achieve this habit. The mere fact that equal temperament is an artificial mathematical compromise, should in itself be sufficient to persuade the tuner that this view is sound, especially when the reasons adduced at the beginning of this chapter are recalled. Until one knows practically the true beauties of pure intonation, the almost equally strong virtues and vices of equal temperament will in neither case be duly appreciated.

Any one who has had the privilege of listening to a first-rate string quartet or to a really good

unaccompanied chorus, will understand why pure intonation, once recognized, is ever after treasured in memory.

Chapter V

MECHANICAL TECHNIQUE OF TUNING

The art of tuning the piano comprises two distinct and separate elements. The part of the tuner's education which relates to the science of this art has already been discussed in full in the previous chapters. We must now consider what may be called its general mechanical technique, including the special subject of the tools required, and their manipulation.

The Raw Material. The raw material with which the tuner works may be described for practical purposes as consisting of the strings, the wrest-pins or tuning-pins, the wrest-plank or pin-block, and the tuning hammer. The piano action, the key-board, the wedges for damping the strings, and the tuning-fork may alike be considered, for the present, as accessory to, rather than as part of, the essential material. Let us now consider these in order.

String Conditions. It is well known, of course, that the pitch of a string—that is to say, its frequency of vibration—varies as the square root of its tension. Hence, if the tension be increased, the frequency is increased likewise; while if the ten-

sion be relaxed, the pitch is lowered. Now, the tension of a string is increased by tightening it on its pin, that is, by turning the pin so as to stretch the string more tightly; and is relaxed in precisely the opposite way, that is, by slacking the string.

String and Pin. The piano string is wound so that the pin lies, as seen from the front, to its right on an upright piano and to its left on a grand. But relatively the positions are the same, and the difference stated is due to the different position from which we view the strings on an upright and a grand respectively. It would be better to say that the string is always on the treble side of the pin in a horizontal, and on the bass side in an upright piano. When the tuner wishes to raise the pitch of a string he turns the pin so as to wind up the string on it. To lower the pitch he turns the pin so as to unwind the string.

The mechanical problem therefore is to turn the pins in the wrest-plank in such a way as to adjust the pitch of each string to the requirements of the equal temperament at the standard of pitch agreed on.

The Elements. In following chapters, I give a general description of piano construction and necessarily include some remarks on the functions of all the parts herein mentioned. In the present chapter, however, I shall treat these only with relation to the tuner's work.

The String. The piano string varies in length inversely as its pitch and may be from 2 inches to 80 inches long, according to its position in the scale and the size of the piano. Steel music wire is used, varying in diameter from 0.031″ to 0.067″. The lower strings are wound with steel or copper overwinding or covering. The tension at which the strings are stretched varies within the limits of 100 and 275 pounds; but it would be fair to name as an average range of tension per string in modern pianos 150 to 160 pounds, although there is much inequality as to details.

Bearing. The opposite end of the string is passed around a hitch pin in the iron frame. In order to transmit its vibrations to the sound-board the string passes over a wooden bridge provided with staggered pins, so as to give it a side bearing. At the end near the tuning pin the string passes over a wooden or iron bearing bridge which determines the upper, as the sound-board bridge determines the lower, extremity of its vibrating length. This upper bridge gives an up and down bearing to the string. It is important that these points be kept in mind and the student carefully study the construction upon an actual piano; which I am presuming he has at hand.

The Pin Block. The torsional stress on the pin being what it is, considering the high tension at which the string is commonly stretched, it follows

that efficient means are necessary to maintain the pin in a given position under this stress. The common method is to drive the pins into a wooden block called the wrest-plank or pin-block; which is built up by cross-banding several strips of hard wood. Such a block, when drilled for the reception of the tuning pins at right angles to the plane of the banding, gives an exceedingly stiff bedding, for the cross-banded strips present alternately end-grain and cross-grain, making a structure which interposes a very great frictional resistance to the rotative movement of the pin. It is the frictional resistance which is responsible for the pin holding its position, and hence for the string remaining at a given tension.

The Tuning-Pin. The tuning-pin is a stout steel rod, almost uniform in diameter from end to end, and threaded with a light fine thread. One extremity is bluntly pointed, while the other is squared off to receive the tuning-hammer and pierced for the insertion of the end of the string. It is customary to wrap the string around the pin in three or four coils.

The Bridges. The sound-board bridges carry the strings between short staggered metal pins, so that each string is diverted from its line of direction and carried on from the bridge to the hitch-pin on a line parallel with the original line. The side-bearing thus given to the string is intended

to insure its tightness and steadiness on the bridge.

The upper bearing bridge sometimes is in the form of a separate stud or "agraffe" for each string, and sometimes consists of a ledge cast in the plate over which the string passes, to be forced down into a bearing position by a heavy pressure bar screwed over it. The object is to give bearing to the string. The "capo-d'astro" bar is simply the pressure-bar arrangement cast in one piece. The student will be well advised to study all these constructions on the piano at first hand.

The Tuning-hammer. The tuning-hammer, with which the actual turning of the pin is accomplished, is a steel rod carrying a head bored to receive the pin. The hammer is placed on the pin, which is turned by pressure of the hand on the hammer handle in the required direction. There are many interesting points about the manipulation of the hammer, however, which must now be considered.

The mechanical problem relates to the turning of a pin acting under a combined tensional and torsional strain; in other words, a pin which is being simultaneously pulled towards the sounding-board bridge by the string, and twisted around by the tuning-hammer. If the wrest-plank is well made, the pin will resist successfully both of these strains and when turned by the hammer will retain

its new position. But in order that this should be so it is necessary to acquire a certain technique of manipulation.

Manipulating the Hammer. The implement used for turning the pins and known as the tuning-hammer presents, by its very shape, the constant temptation to manipulate it as if it were a wrench. The resistance that the pin and string impose against turning is sufficiently great to cause a novice nearly always to twist and wrench at the pin in the effort to turn it. Now, it must be remembered that the distance through which the pin is turned is so very slight that where it has been tightly driven, or presents any other obstacle to free turning, the hammer nearly always gives too hard a twist or pull, so that the pin, after sticking, turns too far. In an upright piano the tuner stands in front of the pins, which are about on a level with his chest, and his natural inclination, of course, will be to pull downwards and outwards on the pins whilst attempting to turn them, in such a way as to drag the lower surface of the pin against the bushing in the iron plate and so gradually wear away the bushing and the wrest-plank hole and finally loosen the pin altogether. In order to overcome these possible faults, the student will have to work out his own method of manipulation, bearing in mind always that his object is to turn the pin and not merely to bend it. If he merely bends it he

may alter the string tension enough to change the pitch as desired; but a smart blow on the piano key will soon knock the string back again where it was before. That is why young tuners do not tune "solidly." They do not turn the pins; they merely bend them. I shall offer the following suggestions regarding the general handling of the piano in tuning, out of my own experience, with the understanding that I do not put them forth as rules, but only as notions which have been found practical in one man's work.

1. *Length of Hammer.* Other things being equal, the experience of the best tuners points to the use of a short handled hammer, instead of a long one. I prefer a handle not more than 12 inches long.

2. *Position of Hammer.* The hammer should be held nearly vertical when tuning upright pianos, and it is well to rest the arm, as this tends to give better leverage.

3. *Turning the Pin.* In attempting to turn the pin, do not jerk the hammer back and forth, nor on the other hand, use it like a wrench, but rather try to turn it by gently impelling it in the desired direction, feeling it all the time under the hand and avoiding the mistake of pulling down or backwards on it while turning.

4. *Use of Left Hand, in Upright Pianos.* The best way of making sure that the pin is not pulled

downwards while the string is being sharped is to hold the tuning hammer in the left hand. The pin is then raised in the process of sharping; which is as it should be. In any case, the hammer should be held vertical, or still better, inclining slightly over to the bass side. The above applies to the upright piano only.

5. *And in Grand Pianos.* In a grand piano, to tune with the right hand is best on account of the position of the tuner with relation to the strings; which is opposite to the position with reference to the upright. But the highest treble strings, on account of the peculiar construction of the grand piano, are most conveniently tuned with the hammer held in the left hand.

6. *Tuning Pure Intervals First.* All intervals that are to be tempered should be first tuned pure and then raised or lowered.[1] Other things being equal, it is better to tune slightly above the required pitch and let the string slack back; which can be assisted by a smart blow on the key. Coaxing the string up to pitch usually involves its slacking off as soon as the piano is played.

7. *Strings Hanging on Bridges.* Strings often hang on the belly bridge and on the upper bearing. The waste ends at either extremity sometimes cause trouble. The tuner must acquire the habit of so tuning that the string is pulled evenly

[1] See page 83.

through its entire length, from tuning-pin to hitch-pin, maintaining the tension of all its sections uniform. To be sure that the pin is thoroughly turned gives the best assurance that the above requirement has been fulfilled.

8. *"Pounding" Condemned.* I do not believe in brutally pounding on the keys of a piano in an effort to "settle the strings." It is quite uncertain how much the strings can be "settled" in any way like this; and the process is objectionable in every other way.

9. *Muting.* The simplest way of muting the strings is by using a long strip of felt to stop off the outside strings of the triples and the alternate strings of the doubles, from one end of the piano to the other, before the tuning begins. Then the temperament octave may be tuned on the middle string of each note and the octaves up and down therefrom; after which the outside strings of the unisons may be tuned all together. If, however, for any reasons such as those mentioned below, this produces uneven strains on the plate, the unisons can be adjusted section by section.

10. *Position at the Piano.* All things considered, it is better to stand up to tune all pianos, even grand pianos. The practice of sitting to tune upright pianos is certainly to be condemned, as it leads to slovenly handling of the hammer and general slackness.

11. *Raising Pitch.* In raising the pitch of a piano, one should go over it at least twice, the first time roughly, the second time smoothly. If the amount of rise required is very great the piano will need three tunings at once and another shortly after. Arrangements should be made with the owner of the piano in accordance with the extra amount of work to be done.

12. *On Old Pianos.* Raising the pitch on old pianos is always risky, as strings are likely to break. In emergencies, rust may be treated, at the upper bearing bridge and hitch-pins, sparingly with oil. But oil is only to be used in emergencies, and with the utmost care to see that it does not reach the wrest-plank or sound-board bridges.[1]

13. *Lowering Pitch.* In lowering the pitch, not less than three tunings will usually be required. This work is even more delicate than the above and needs even more care. The first tuning should be merely a rough letting down. Then the second may be a rough, and the third a smooth, tuning. But it is well to have an interval of a day between the second and the third tunings.

14. *Gang Mute.* Even if a felt strip for a whole section is not used, it is advisable to have the

[1] Various manufacturers of piano wire in the United States and abroad have produced rust-resisting wire, either galvanized or plated with cadmium. The latter metal gives the most efficient results. Costs of manufacture so far have been very high, which has prevented a large demand from piano manufacturers. Alloyed ("stainless") steels have not hitherto been suitable.

entire temperament octave wedged up whilst tuning it, so as not to have it disturb unisons after they have been tuned. It is usually necessary to make various corrections in the temperament octave as it is being tuned.

15. *Uniform Pitch.* Uniformity of pitch is a desideratum. Every tuner should have a good tuning fork accurately rated to A 440 or to C 261.6, kept carefully in a felt-lined box and carefully guarded from rust. He should tune to this pitch whenever possible, but must not make the mistake of trying to adjust all pianos to one pitch. It cannot be done.

16. *Theatre Pianos.* In tuning pianos for use in theatres with orchestras, it is advisable usually to tune by a few audible beats, above the pitch of the instrument which is used as a standard. This instrument is usually the clarinet or cornet (in symphony orchestras the oboe), which rises in pitch as it warms in the course of playing.

17. *False Beats.* The worst single enemy the tuner has is the string with false beats. In a good piano factory such strings are taken out and replaced before the piano leaves the premises. Sometimes faults in the scale make for strings that beat when sounded alone. This beating arises through sections of the strings being unevenly strained, whereby the corresponding partial tones are thrown out of tune. Such uneven strain may

be the result of a twist put in the wire during the stringing, or of uneven thickness of the wire. When false beats are encountered, sometimes the tuner will find he can neutralize the beats by tuning the string slightly off from the other two of the triple. If no such expedient will work, then the strings must be left alone. Such false beats are especially to be found in the upper treble.

18. *Bass Tuning.* The real fundamental tones of the lowest strings are not actually heard. We hear instead upper partials thereof. Hence it is very often impossible to tune bass octaves by mere audition of beats between coincident partials. In this condition of affairs the tuner may tune by testing the tenths, which is a good plan, or by isolating some partial and testing it with the corresponding note above. To tune a clear bass is sometimes impossible.[1]

19. *Test Intervals.* All the tests recommended in the previous chapter should be used constantly during the progress of the work, for otherwise the tuning will not be good. The most prolific source of imperfection lies in the accumulation of exceedingly slight errors; which soon mount up to intolerable mistuning. Constant testing, note by note, therefore, is absolutely essential.

20. *Sharp Treble.* The temptation to tune the treble notes too high is one constantly to be

[1] Cf. the discussions in Chapters 2, 3 and 4.

avoided, for it is constantly present. Careful testing alone will cure the tuner of this error, which is insidious and habit-forming.

21. *Lastly.* Not twenty, but an hundred and twenty, rules or suggestions like these could easily be laid down; but I prefer to leave the subject here. The student will learn at least one more; the value of patience.

"Style." The student will also determine for himself, as time goes on, the characteristics of what may be called his special "style." Tuning is an art and one which suffers more through being misunderstood than through any other single condition. The fine tuner is an artist in every sense of the word and the mental characteristics he must possess are such as not every one can hope to have.

Understanding and Patience. Understanding and patience are the foundation of the tuner's art and for my part I am not sure to which of these qualities I should award the primacy. Certainly it is true that without understanding the tuner is groping in the dark; while without patience he is already condemned in advance to failure in any attempt to do artistic work.

Experience. Experience too, is vastly important. The most talented student of the art finds that there is a mechanical technique to be mastered in tuning, just as in playing the piano. The necessary delicacy of wrist and arm, the neces-

sary intuitive feeling that the pin has been turned as it should be; the necessary exquisite delicacy of ear:[1] all these faculties are the product of patience, experiment and practice. The novice cannot expect to possess them; nor can he have any reason for being disappointed when he finds, as he will find, that to gain anything worth gaining, one must work—and work hard.

"Playing the Game." Still, it also remains that when one does take the trouble to play the game as it must be played, the reward is certain—and by no means contemptible; even when measured by mere money, the lowest of standards. To-day really good tuners are as scarce as they were fifty years ago. The tuning of every day is not good, usually; and the artistic tuner will find a hearty welcome, and adequate compensation, almost everywhere.

Finally. All that can be taught by words I have now set forth. But mastery comes only through experience, combined with patient study and application. Various matters incidental to the art which do not come within the scope of "tuning" proper are treated in the following chapters of this book.

[1] "Delicacy" here means rather "power of discrimination" than mere intuition. What is usually called a "musical ear" is nothing more than, at best, a feeling of tonality sometimes extending so far as to unaided identification of individual tones and tonalities on hearing them; and at worst, an inclination towards simple melody, harmonically bare. The tuner's audition is acoustical, not artificially "musical." The ordinary "musical ear" is of little value to him.

CHAPTER VI

THE MODERN PIANO

Scope of This Chapter. The piano is the most familiar of musical instruments and one of the most accessible for purposes of examination. In the following pages, I shall assume that the reader has a piano at hand and will follow me throughout, with it as a model. Such a method will be found more satisfactory than if I asked the student to follow me with the aid merely of a few illustrations. I shall not undertake any critical examination of the details of piano construction, for this is the province of a special technical treatise,[1] but shall confine myself to describing the features of the modern piano in a manner calculated to be of the greatest assistance to the tuner and repair man.

An Instrument of Percussion. The piano is a stringed instrument; and to this extent belongs to the same general family as the violin. But its strings are excited by blows inflicted directly by a hammer and indirectly, through a mechanism called the "action," by the performer's hand. Hence the

[1] Such as "The Acoustic Design and Construction of the Piano" (1928), by the present writer, throughout this book referred to as "Acoustic Design."

piano is also an instrument of percussion and belongs to the same general family with the dulcimer, the xylophone and the drums. This last fact is of great importance, for it is impossible to understand the peculiarities of the piano unless we entirely forget its incidental likeness to other stringed instruments and concentrate our ideas upon the outstanding fact of percussion as the cause of the sounds evoked by it.

Upon the fact that the strings are violently struck, instead of being bowed or plucked, rests the entire character of the piano, making any comparison of it with the violin or other stringed instrument absurd. This is especially true with regard to the sound-board.

Three Elements. The piano proper comprises three elements; the scale, the sound-board and the hammer action. All other parts are entirely incidental and accessory.

Scale. The scale of the piano consists essentially of the set of strings which are struck by the hammers. There are eighty-eight keys in the keyboard of the piano and thus eighty-eight separate musical sounds. The strings are grouped three to an unison throughout some five octaves of the range, and thence in double grouping (2 to a note) downwards to the lowest bass. The last ten or twelve at the extremity of the bass are usually single strings.

Now it will be understood that the strings of the piano increase in length and weight as the scale descends. The highest note on the piano (C_{ss}) is evoked by a string some 2 inches long, and this length rather less than doubles at each octave descending, until the lengthening process is brought to a stop at the size limits of the piano. This lengthening increases the weight of the descending strings until at about five octaves below C_{ss}, it becomes necessary to shorten the remaining strings between this point and the extreme bass on account of the size limits mentioned above. The requisite low frequency therefore must be had by overweighting the shortened strings; which is done by covering them with iron or copper wire. This covered section is usually strung cross-ways over the treble strings and is therefore called the overstrung section or the "bass" section.

Now the immediate point is that in order to maintain this enormous mass of steel wire between fixed points and to make it capable of withstanding the hardest blows of the hammers, (1) the tension at which each string is stretched must be high and (2) in consequence, an elaborate structure must be provided for the purpose of supporting this mass under this high tension. The pull on each string averages not less than 160 pounds, taking modern pianos by and large. The total tensional strain therefore

is not less than 36,000 pounds on the average; and this strain must be borne by the supporting structure.

Upright Piano, Plate and Back. The supporting structure in the upright piano consists of a relatively thin plate or frame of metal backed by a decidedly heavy and massive framing of wood. The shape and dimensions of this plate vary with the size of the piano and the peculiarities of the individual scale plan. The back consists of three or more wooden posts crossed at the top and bottom by heavy planks. The top plank is faced on the surface nearest the strings by a specially prepared wooden block or "wrest-plank," into which are driven the tuning-pins which fasten the upper extremities of the strings and which the tuner turns when adjusting the pitch of the piano; "tuning the piano" as we say.

The iron plate covers the front of this massive wooden back and the sound-board is fastened to the back with the iron plate over it.[1]

Grand Piano; Plate and Back. The supporting structure of the grand piano is somewhat different. In the upright the sides and the casing generally are simply attached to the fundamental structure known as the back. But in the grand piano the whole case is glued around a rim

[1] The method of gluing the sound-board to the back and all similar technical details may be found described in "Acoustic Design."

of cross-banded veneers which in turn encloses another rim, into which runs the system of braces and struts which comprises what corresponds to the upright back and on which sound-board and plate are laid.

First-hand study of pianos in grand and upright form will reveal clearly to the student all these details.

Sound-board and Bridges. The sound-board of the piano is the resonating apparatus which amplifies and modifies the string-sounds, so as to endue them with the characteristics of piano tone. It is an open question how much influence the sound-board exercises in the development of tone. My own hypothesis has been for long that the sound-board is a true amplifying vibrator; and that the string imposes upon the board the particular wave-form which its own vibration evokes.[1]

From the tuner's point of view, the chief present interest of the sound-board lies in its physical character and its behavior under use. Even a cursory examination of the sound-board and of the bridges which cross it carrying the strings, indicates clearly that two essential conditions must exist if the board is to perform its resonating duty well. The strings must be maintained on an adequate up-bearing and side-bearing. The board must be resilient, but also stiff, in a sense. It must be

[1] Cf. "Acoustic Design," where the whole subject is very thoroughly discussed.

arched upwards to maintain itself against the immense down pressure of the strings, but also it must be built so that the necessary arching shall have no injurious effect upon the wood-fibres, with consequent splitting or cracking. It will easily be seen then that the sound-board of the piano is a structure of exceeding delicacy, called upon to perform difficult and laborious tasks.

The strings are carried over the sound-board on two wooden bridges, one for the overstrung bass and one for the remaining strings. It is customary to construct these bridges of cross-banded hard maple veneers, to avoid splitting. The strings in their passage across the bridges are given side-bearing by means of suitably driven pins. These bridges are glued on the sound-board and secured from the back thereof by means of screws.

Ribs. The sound-board is ribbed with strips of the same lumber (spruce) which is used for the body of the board. The object of ribbing is (1) to facilitate the impartation of a proper curve, or arch (called usually the "crown") to the board, (2) to facilitate the transmission of sound vibrations across the grain of the board and (3) to strengthen it against the string-pressure. Ribs are usually 10 to 14 in number and cross the board diagonally, from the top of the treble to the bottom of the bass, side, at right angles so far as may be practicable to the grain of the wood.

The foregoing description applies equally well to grand or upright pianos.

Hammers. The strings of the piano are excited by blows inflicted on them by what are called "hammers." Each hammer consists of a molded wooden head covered with a special kind of felt, and varying in size and thickness from treble to bass, the heaviest hammers being of course those in the bass. Important considerations are (1) the position of the hammer with reference to the point at which each string is struck, and (2) the nature of the mechanism whereby the performer translates his desires into mechanical action upon the hammer.[1]

"Touch." All that which is known by the general name of "touch" in relation to the playing of the piano means, ultimately, control of the piano hammer. A great deal of confusion on the part of tuners, not to mention musicians and the lay public, would be altogether swept away if only it were realized that in piano playing the control of the string's vibration, which of course means control of the wave-form and hence of the sounding-board's vibration, and hence lastly of the volume and quality of the tone, is entirely a matter of the hammer. The weight of the hammer, the nature of its material as to density, etc., and the arc of travel through which it turns, together with its

[1] Cf. the complete discussion in "Acoustic Design."

velocity, are the controlling factors in tone production. This turning of the hammer in obedience to the depression of the piano key is the province of what is called the "Action" of the piano.

Action. The "action" of the piano is the mechanism interposed between hammer and performer. It consists essentially of a set of digitals or finger-keys, one for each sound in the compass of the piano, and an equal number of lever-systems, consisting of levers turning in arcs of circles, one to each key, operating the hammer. When the key is depressed, the hammer is thrown forward, trips before it touches the string, is carried to the string by its own momentum, and instantly rebounds. The string is allowed to vibrate so long as the key is depressed.[1]

Damper Action. The so-called "damper" is a piece of molded wood faced with soft felt, which presses against the string, but is lifted away therefrom as soon as the key is depressed. The damper allows the string to vibrate freely until the key is released, when it at once falls back on the string and silences it.

For the purposes of artistic piano playing, however, it is necessary very often to take advantage of the sympathetic resonance of the sound-board by allowing the tone emitted by one or several

[1] Cf. Chapter VIII for complete discussion of these points.

string-groups to be strengthened, colored and otherwise enriched by the simultaneous sounding of other strings whose fundamentals are true partials to the originally sounded strings. When the entire line of dampers is lifted from the strings and held away from them by suitable mechanism, this property of the sound-board comes into play, and the warm color thus imparted to the tone constitutes one of the most valuable elements in piano playing.

In order to permit this advantage, the line of dampers is adapted to be pushed back from the strings (or in the grand piano, lifted up from them) by means of a rod actuated by a simple lever system which terminates in a "pedal" operated by the right foot of the performer. This lever system is called the "trap-work" of the piano and is situated under the keyboard in the grand piano, with the pedals arranged in a frame-work known as the "lyre"; while in the upright the pedal and trap-work are placed at the bottom of the piano on what is called the "bottom-board." The pedal is convenient to the performer's right foot and is called the "sustaining pedal": sometimes, wrongly, the "loud pedal."

Soft Pedal. In the grand piano the keys and action are put together on a frame which can slide transversely. Depressing a second pedal slides the action towards the treble, so that each

hammer now strikes only two strings of each triple, and one of each double, group. The effect is to soften the sound and modify the tone-color. Similar trap-work is used between pedal and action, placed alongside the sustaining pedal action. The second pedal is placed conveniently to the performer's left foot and is called the "soft pedal."

In the upright piano the arrangement is the same except that instead of shifting the action, the pedal acts to push the hammers forward closer to the strings by means of a rod which rotates the rail against which the hammer-shanks rest.

Sostenuto or Tone-Sustaining Pedal. On grand pianos, and occasionally on uprights, is to be found a third pedal situated between the other two and arranged to hold up dampers which are already lifted by the action of the performer in playing on the keys; and to hold them up as long as desired. A rod is rotated when the pedal is depressed, which catches against felt tongues on any dampers that may have been raised, and holds them up. So if the performer wishes to sustain a chord after his fingers have quitted the keys, he depresses this pedal after he has struck the keys and thus allows the strings to vibrate accordingly until the pedal is released.

Middle pedals in upright pianos are sometimes arranged for the same purpose, and sometimes lift

the bass section of dampers. Sometimes they operate a "muffler," which is a strip of felt that can be thrown between the hammers and the strings for the purpose of "muffling" the sound. This is useful for practice purposes.

Casework. The case of the upright piano consists of the following parts:

Sides: Glued on to the sides of the back.

Arms: Extending from sides to support key-bed.

Key-Bed: Upon which the key-frame is laid.

Toes: Entending from bottom of sides to support trusses.

Trusses: Resting on toes and holding up key-bed. Sometimes called the "legs."

Fall-Board: The folding lid over the keys. The double folding type is now usual and is called the "Boston" fall-board. The older type or single lid is called the "New York" fall-board.

Shelf: Laid over fall-board to support music.

Name-Board. Resting over keys to support single type fall-board.

Key-Slip: Strip in front of keys.

Key-Blocks: Heavy blocks at each extremity of keyboard.

Top-Frame: Folding or fixed frame, often elaborately decorated, which supports music and conceals piano action and hammers.

Bottom-frame: Similar frame to the above, covering trap-work and parts of piano under key-bed.

Pilasters: Decorative pillars sometimes placed on either side of top-frame to support it.

Top: The folding lid which covers top frame and finishes off the casework of the piano.

Bottom-Rail: Rail running across the bottom of the casework, in which the pedals are housed.

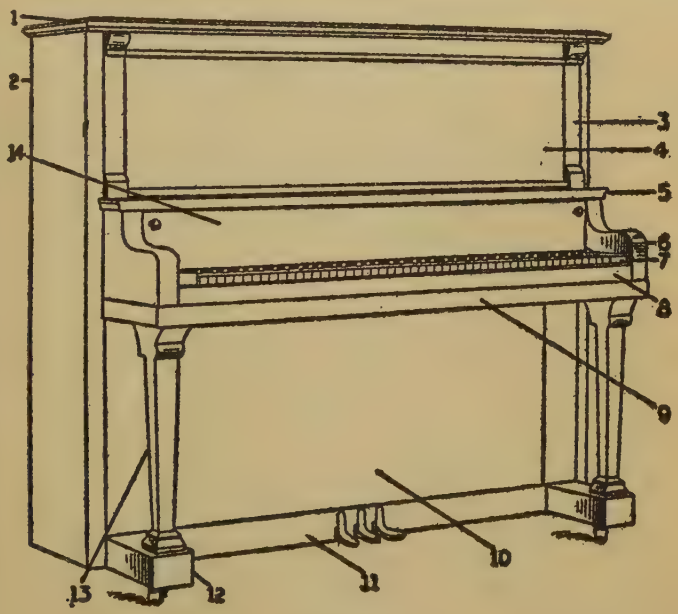

FIGURE 15

1. Top.
2. Side.
3. Pilaster.
4. Top frame.
5. Shelf.
6. Arm.
7. Key-block.
8. Key-slip.
9. Key-bed.
10. Bottom frame.
11. Bottom rail.
12. Toe-block.
13. Truss.
14. Fall-board.

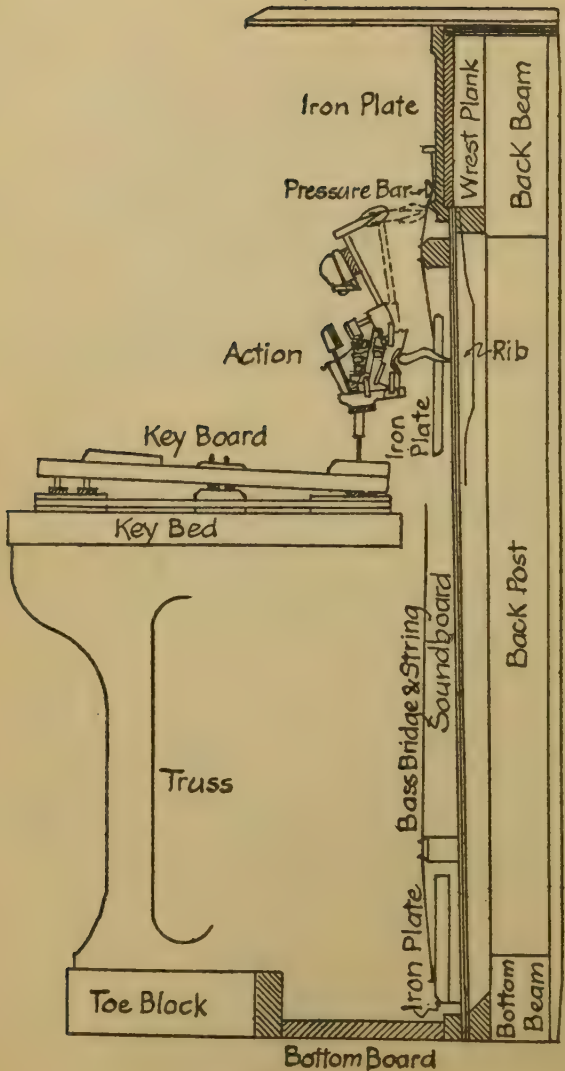
Iron Plate
Pressure Bar
Action
Key Board
Key Bed
Truss
Toe Block
Bottom Board
Iron Plate
Bass Bridge & String
Sound board
Iron Plate
Wrest Plank
Back Beam
Rib
Back Post
Bottom Beam

FIGURE 16

Bottom-Board: Board on which trap-work is mounted, behind the bottom-frame.

Names of External Parts. Although the piano is such a familiar article there is a great deal of confusion as to the names to be applied to its various parts. In Figure 15 are shown the external or visible parts of an upright piano with the proper name for each appended.

The various case parts of the grand piano are of course largely similar, but the different position of the scale necessitates modifications, which involve some changes in names and positions of parts, as shown on page 129.

Names of Internal Parts. In order to provide the reader with a list of correct names for the various internal parts of the piano, the illustration on page 126, Figure 16, shows a cross-sectional view of an upright piano.

The rear view shown on page 128 indicates the position of the various elements in the back frame and the rear of the sound-board.

The grand piano, Figure 18, page 129, can be shown only as is here done by means of a cross-sectional illustration. The differences, such as they are, which exist between the two types of piano, are thoroughly explained in the pages which follow.

Finish. Modern pianos are elaborately finished with a highly polished surface. The base of this finish is several coats of varnish, which are rubbed

down and then re-varnished with what is called a "flowing" coat of very heavy varnish. This is again rubbed down, first with pumice stone, felt pad and water, then with rotten stone, felt pad and water and then with the hand. The final finish is given by rubbing with lemon oil, which is lastly wiped off with cheese cloth wrung out in alcohol.

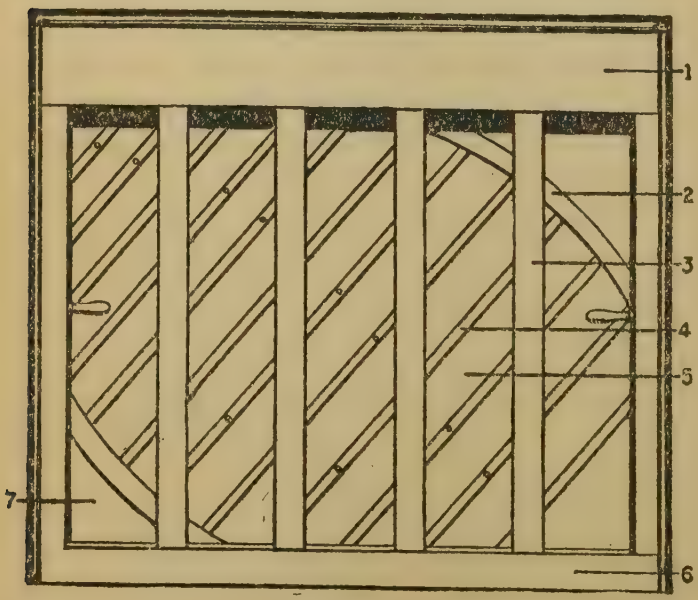

FIGURE 17

1. Top block of back, behind wrest-plank.
2. Limiting rim of sound-board.
3. Posts.
4. Ribbing.
5. Surface of sound-board.
6. Bottom rail of back.
7. Limiting rim of sound-board.

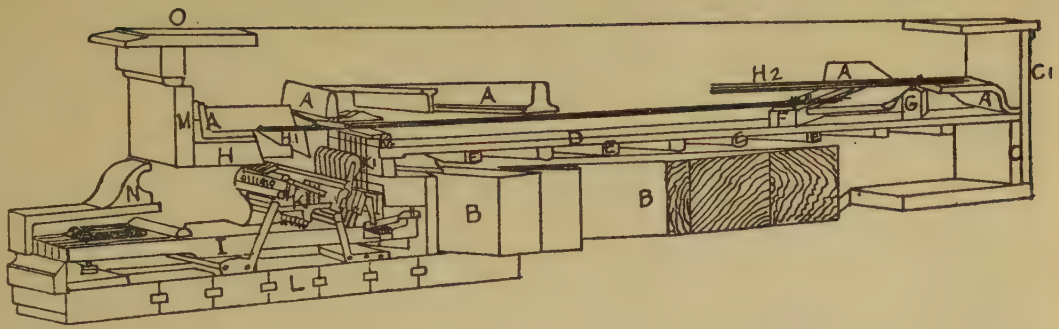

FIGURE 18

Cross-section, Steinway Grand.

A. Iron plate, bars and body.
B. Beams holding rims in shape.
C. Rim (inner).
C_1. Rim (outer).
D. Sound-board.
E. Ribs.
F. Treble bridge.
G. Bass bridge.
H. Wrest-plank.
H_1. Treble strings.
H_2. Bass strings.
I. Keys.
K. Action.
L. Hammers.
M. Front-board.
N. Fall-board.

Although this finish is very beautiful it does not retain its brilliancy long under domestic conditions. In the remarks on piano repairing I have made several suggestions concerning the repair of damaged varnish work.

This brief description of the modern piano has been intended to furnish the student only with an explanation of the relation of the various parts to each other and the correct functions of each. More thorough studies are made in following chapters of certain elements which the tuner requires to understand in completeness and the present chapter will be perhaps most useful in providing a convenient peg on which to hang them. Although it fulfills so humble a purpose, however, it will not be without its value if it impresses on the reader's mind the great truth that the piano, as it stands, is by no means to be regarded as the fruit of sudden inspiration but rather as the contemporary stage in a long process of evolution. The history of the instruments which preceded the piano in point of time and which in system are its ancestors, shows plainly that the invention of the hammer action by Cristofori in 1709 was merely the culmination of a long series of efforts on the part of many great craftsmen, looking towards the production of a musical stringed instrument capable of doing for domestic use what the organ has always done for the church: namely, furnish com-

plete command over all existing resources of harmony as well as melody. The piano as it stands today is the crown of three centuries of endeavor; but it is by no means certain that it will not yet be modified much further. No one can pretend that the piano is a perfect instrument. Its tempered intonation, its rather hard unmalleable tone, its lack of true sostenuto, all represent defects that must in time be improved out of existence. Meanwhile, we have to take the piano as we find it, realizing that after all it is a very fine and a very wonderful instrument.[1]

Materials Used in Piano Construction.

Woods:	Used In
Mahogany.	Veneers for cases.
Walnut.	Veneers for cases.
Oak.	Veneers for cases.
Circassian Walnut.	Veneers for cases.
Bird's Eye Maple.	Veneers for cases.
Maple.	Veneers for cases. Wrest-planks. Backs. Hammer moldings and shanks. Hammer rails, dowels, etc.
White Wood.	Body of case work.
White Pine.	Key-frames and keys.
Spruce.	Sound-boards, posts, ribs.
Pear. Holly. Sycamore. Cedar. Mahogany	Various small action parts.

[1] The reader who desires to study the extremely fascinating history of the piano may find an extensive literature on the subject. Hipkins is the best authority by all means. See bibliographical note at the end of this volume. "Acoustic Design" opens with a rather comprehensive historical sketch tracing the development of the percussion principle from the psaltery and dulcimer to the clavichord and the piano.

Materials Used in Piano Construction.—Cont.

LEATHERS:	
Doeskin.	Various action parts.
Elkskin.	
Buckskin.	
FELT AND CLOTH:	
Green and White Baize.	Key-rail cloth, punchings.
Tone Felt.	Hammers.
Damper Felt, hard.	Bass dampers.
Damper Felt, soft.	Treble dampers.
Flannel.	Casework, punchings, fall-board strips, name-board strips, stringing.
IVORY.	Top of white keys.
IRON.	Iron plate, action brackets, bolts and general hardware.
STEEL.	Action angle rails, plates, trap-work, springs, steel wire for strings, etc.
COPPER.	Covering wire for bass strings.
BRASS.	Action-springs, pedal feet, rods.
GRAPHITE.	Lubrication of action, etc.

Various other materials are used in small quantities, for individual manufacturers have their own special methods which require special materials. But the above includes the principal materials common to all pianos.

CHAPTER VII

SOUND-BOARD AND STRINGS

Quite as characteristic of the piano's individuality as the hammer action itself, is the apparatus of resonance, or, as we more usually call it, the sound-board. The piano is a stringed instrument and thus claims kinship with viols and lutes and all their descendants; but ever so much more it is a resonance instrument and a percussion instrument. In fact, the true character of the piano cannot be rightly apprehended until we have realized that the string-element is incapable of realizing its capacities save through the sound-board. The piano is just as much dependent upon resonance as upon the prior vibration of the strings. Without the sound-board the piano would have neither power nor color to its tones. Moreover, variations in the construction of the sound-board involve parallel variations in the tonal values of pianos, of such character as to convince us that we must accord to the combined tone-apparatus which we call "sound-board and strings," entirely individual peculiarities and functions.

Definition of Tone-Emission Apparatus Functions. The object of the tone-emission apparatus

of the piano may be described as follows: to produce the characteristic piano tone, through the vibration of the strings in response to the percussive action of the hammers thereon, and through the resonating functions of the sound-board, whereby the original string wave-forms are combined, amplified, and transformed in quality as required for the purpose indicated.

This is not a neat definition perhaps, nor is it uncommonly accurate in all its parts; but for the present it is perhaps the best that can be assimilated. Later on we shall improve and refine the details with better understanding.

Piano Tone. The feature of the piano which distinguishes it generally from all other musical instruments, and specially from all other stringed instruments, is the peculiar character of its tone. This is, to an extent, of course, hard and unmalleable. It possesses neither the plasticity of the violin tone nor the bitter-sweet gayety and lightness of the guitar. It is solid, yet evanescent, hard, yet capable of infinite graduation in intensity. Lacking the serenity and majesty of the organ diapason, it is pre-eminent in obedience to touch. The pianist cannot indeed sustain his tones, nor swell or diminish them at will. Here both organ and violin surpass the piano. But the pianist has a touch control over the dynamics of his instrument which the organ entirely lacks and

can even, within rather narrow limits indeed, vary the color of the sounds emitted by the piano. When brought forth by a good performer this tone has qualities highly attractive, which, combined with the convenience of the instrument, its capacity for complete musical expression in all possible harmonic relations, and its moderate price, have made it supreme in popularity. Let us then see just how this peculiar tone is produced.

Acoustical Definition of Piano Tone. Speaking from the viewpoint which we have adopted in Chapter II, it may be said that piano tone is the effect of a wave-form induced by hammers striking upon heavy high-tensioned stretched strings at pre-determined points on the surface thereof: these waves having definite forms, which are amplified and to some extent modified by the resonating power of the sound-board. The first important feature is that the piano tone is produced by the strings being struck; thus distinguishing the piano from all other stringed instruments.

The string is struck. As we have already found out[1] a string stretched at high tension and struck by a piano hammer, is thrown into an extremely complex form of vibration. This vibrational form consists of the resultant of a number of simple forms, which in turn are the effect of the string's vibrating in various segments as well as in its

[1] *Supra,* Chapter II.

whole length. In short, the fundamental tone of the string sounds together with a greater or lesser number of partial tones,[1] whenever the hammer makes its stroke. The exact number of concomitant partials depends, partly upon the amplitude of the vibration, which depends in turn upon the intensity of the blow, partly upon choice of the point of contact of hammer on string, and partly upon the stiffness and weight of the string.[2]

"Touch." "Touch," of course is an important element in the control of the exact shape of the wave-form. Tone-color or character, as we are aware,[3] depend upon the wave-form, and that means upon the number and prominence of the concomitant partials. That, in turn, from the "touch" point of view, means the hammer velocity in connection with the rebound thereof. That is to say, control over the wave-form of the string, as finally emitted through the medium of the sound-board, rests, so far as concerns the performer, upon his manner of manipulating the hammer so as to vary the length of time required for it to travel from the position of rest to the string, and back; or in other words, and more roughly, in the

[1] See Chapter II, "Resultant Motion."

[2] The sound emitted is more complex in the bass and less complex in the treble regions. Below E_{20} on most pianos the sound waves lose their definite patterns. Above C_{64} they tend to become simple tuning fork, or fundamental sine curves. The whole subject is discussed in "Acoustic Design," to which the reader is referred.

[3] Cf. "Acoustic Design."

force and rapidity of the actual excitation of the string.[1]

Sound-Board Vibration Demonstrated. So much for hammer and string; but how about the sound-board? The part it plays is very important. Suppose that a long thin rod of spruce wood is made up, sufficiently long to extend the length of one room and into another. Spruce is the wood from which piano sound-boards are made. Suppose that one end of this rod is doweled into one of the ribs of a piano sound-board so that it touches the rear surface of the board and thence runs into the next room, all intermediate doors being stopped off so that ordinarily no sound will come from one room to the other. If the open end of the rod be now brought into contact with the sound-board of another piano, leaving the dampers of this second instrument raised, the tone of the first piano when played will be reproduced in diminished volume, from the surface of the second sound-board. The same experiment may be made by using a violin as the "receiving instrument." It is thus evident that the sound-board of the piano has independently the power of vibrating in all the extraordinary complex of motions that arise, not only as the resultant wave of the complex motion of one string, but as the combined resultant—the re-

[1] See Ortmann's "Physical Basis of Pianoforte Touch and Tone," where this subject is completely and decisively treated.

sultant of resultants—of the motions of many simultaneously excited strings. The motion of a string may be compared with the operation of several forces pulling in different directions. The resultant of these forces—that is, the direction in which the net value of all the forces when compounded, is seen to lie—can be determined mathematically. So also we know that the complex vibration of one string combines into a single complex or resultant curve.[1] And so also we can see that the complex vibrations of two strings, if impressed together upon a sound-board, must combine into a further resultant; a process which can be carried on indefinitely. Thus, while on the one hand the sound-board must be capable of complex forms of motion, on the other hand the mechanical realization of such forms is neither inconceivable nor even particularly difficult to apprehend.

Analogy of the Monochord. If these suggestions have any value, they must tend to give us a reasonably clear conception of a theory which may account for the peculiar operation of the sound-board and may fix definitely its place in the economy of the piano. If, in fact, we keep steadily in mind the truth that no matter how many strings may be struck at any given moment, now how consequently complex their motions may be, these motions always must express themselves on the

[1] *Supra,* Chapter II.

sound-board as a single resultant motion, it becomes clear that such resultant motion is ultimately responsible for the tone.

In the circumstances, we may, without unduly stretching the comparison, suggest an analogy with the monochord. This, as we all know, is a single string stretched between a hitch pin and a tuning pin over a small sound-board, with a moveable bridge which can be shifted so as to change the vibrating length of the string whenever and however desired. Now, this string has in itself the possibility of producing all the sounds which can be had by shifting the bridge. No matter how the bridge be placed, and therefore no matter what segment of the string be vibrating at any time, it is the same string. The same string vibrates always, but the moving of the bridge selects the particular segment which is affected. This fact suggests that the strings of the piano, acting with the sound-board, are selecting vibrators, impressing their own individual vibrations upon the sound-board, either singly or in combination. When a single impression is made, the board repeats the motion exactly as transmitted to it. When a complex of impressions is made, this develops instantly into a resultant motion, compounded of all the motions; or as we might better say, being the geometrical sum of all the motions.

Sound-Board an Amplifying Vibrator. If this be

a plausible hypothesis, from the mathematical viewpoint, it is just as plausible mechanically, for while it may be hard to conceive the sound-board's making a thousand different kinds of motion at once, it is not hard to conceive its surface making a single resultant motion; nor is there any mechanical reason why it should not. For if we consider that the sound-board is a table of spruce, forcibly arched by ribbing its back, and very rigidly secured to the piano all around its edges; and if further we keep in mind that the impressibility of the board is immensely increased through its close contact with the great battery of high tension strings communicating with it through the bridges, we can see that we have in it nothing less than an extremely sensitive vibrator, almost a whole musical instrument in itself, ready to sing as soon as it is kindled into life by the operation of the property of resonance. The sound-board, of course, is a resonance instrument, and it is only necessary to understand just what this phenomenon means in Sound, to complete our appreciation of the sound-board's behavior in use.

Resonance. As I said above, the sound-board is an amplifying vibrator, while the strings are the selecting vibrators. But we cannot stop here. How can the board receive the impressions which are transformed into resultant motions? What, in fact, is this Resonance?

Resonance is the property which sonorous bodies possess of receiving and reproducing vibrations impressed upon them by other sonorous bodies. In the case of the tone-emission apparatus of the piano, the sound-board is placed in contact with the battery of strings stretched above it, which pass over wooden bridges glued on the surface of the board, pressing upon these latter with a heavy down bearing. The strings are brought over the bridges between pins, which impart to them also a side-bearing as they cross. Thus it may be seen that the sound-board is in the most favorable condition to receive any vibrations that may originate in the strings. If it can be shown that the vibrations of a string can actually be imparted to the sound-board, and can cause that apparatus to undergo a resultant vibratory motion compounded from these vibrations, then we shall have the action of the sound-board made reasonably clear.

Now, since the power to resonate is to some extent possessed by all substances which may form sonorous bodies, it will be understood that we are not here discussing any uncommon quality of the piano sound-board. Seeing that the physical nearest cause of sound sensation is the performance of vibratory motion by solid bodies, it follows that resonance must take place wherever that vibration can be transmitted. If, then, we have a body of some material thrown into vibration, it is easy to

see that all other bodies of similar material in contact with it must also vibrate. Whether their frequency is the same as that of the original body will depend upon the comparative masses and other qualities of the two. All elastic substances are capable of transmitting vibrations, themselves partaking of the vibratory motion in the process. So, also, if the two bodies in contact be of different material, it follows that vibratory motion may be transmitted from one to the other, so long as both be elastic enough and contact be maintained. Actual physical contact, indeed, may sometimes, under favorable conditions, be eliminated, and the atmosphere alone be competent to transmit the pulse from one body to the other, as it does from one body to the ear. This latter potentiality is translated into fact only when each of the bodies is very favorably situated for the purpose and extremely sensitive to vibratory impulse. The resonance boxes of two adjacent tuning forks furnish an example of these latter qualities.

We see therefore that there is no mechanical or physical reason why the sound-board should not at least receive the vibrations of the strings. The question therefore becomes this: does the sound-board reproduce them after it has received them; and how?

Composition of Impulses. We have already seen that the most satisfactory hypothesis of the sound-

board's functions is that which considers it as a true vibrator; but the mind does not always grasp easily the idea of this apparently stiff and unresponsive structure reproducing and amplifying the complex vibrations of the strings. Yet a simple illustration will show that this is quite possible.

Suppose we secure somewhere a heavy ball, or a metal weight, like a 10 pound scale weight, and suspend it from a cord so as to form a pendulum. If now the cord be gently agitated until it settles into its normal period of vibration, we can determine just what its natural frequency is. Having done this, we may allow the pendulum to come to rest again, and then begin to direct against it puffs of air from the mouth, timing these so as to correspond with the vibratory motion of the pendulum. For several seconds this will have no effect, but if the work be kept up, gradually it will be observed that the weight begins to stir. Let the work go on, we being always careful to blow on the weight only when its direction of motion is the same as that of the breath: that is to say, blow on it only when it is moving away from one. By degrees, if the puffs of air be timed as directed, the weight will begin to swing back and forth in its regular period and at its regular amplitude or width of motion. This is merely an experimental demonstration of the mathematical fact that if a series of small equal forces be periodically ap-

plied to a given resistance through a given elapsed time, at the end of that time the total force applied will have been equal to the sum of the small forces delivered in one unit of time corresponding to the period of one force. To take a concrete instance, if a series of taps, each one ounce in weight, be delivered at the rate of one per second until, say, 160 of them have been made, the resistance has been operated on with a force, at the end of 160 seconds, equal to a force of ten pounds (160 ounces), operating through one second. Thus we see also that it is quite possible for even the most delicate and minute vibratory motions not only to be imparted to a stiff sound-board but also to throw that board into resultant motion. For if we consider that the middle sounds of the piano are produced by frequencies running from 200 to 800 vibrations per second, we can easily see that what is possible in the extreme case here described is more than possible—nay, is inevitable—in the case of the specially prepared, highly elastic and tensioned sound-board, especially when we remember that the strings, being struck, are set in relatively violent agitation, and communicate a relatively more powerful vibratory impression than can be had by blowing with the breath, on a far more responsive resistance than the weight, at many times the possible blowing speed.

Considerations like these, although they do not

actually demonstrate the hypothesis of sound-board behavior here adopted, do strengthen it and tend to confirm it.

To sum up, we may say that the sound-board and strings of the piano together constitute the tone-emission apparatus, that the sound-board is the secondary or amplifying vibrator, that the strings are the primary or selecting vibrators, and that the vibrations of the sound-board are resultant single vibrations due to composition of the complex of vibrations proceeding from the strings, just as the latter themselves are resultants of the complex of segmental vibrations which takes place in the string when it is struck. This hypothesis seems to meet the facts fairly.

In making this analysis I have wished to prepare the reader's mind for an examination of sound-board construction, and especially to show reasons for some of the methods that have been worked out by piano makers. The problem of practical construction is to provide a resonance table that will not merely take up in resultant vibration the impressed vibrations of the strings, but also will properly amplify these as well as reproduce their forms. In other words, the sound-board must not only reproduce the characteristics of the tone, but amplify it too. We need quantity as well as quality.

Amplification. Amplification of the wave-forms

is, of course, a natural consequence flowing from the large area of the sound-board and the consequent relatively great quantities of adjacent air which can be put in vibration. The sounds originally impressed on the board by the wave-forms of the strings are therefore intensified.

Proper Vibration of the Sound-Board. It is evident from what has already been said that the piano sound-board is a sensitive vibrating instrument and therefore must possess a proper period of vibration all its own. That this is so is plain from the facts of the case. The board is arched, or crowned, by means of ribs planed arch-wise and glued to its back, so as to draw the front surface into tension and press the rear into compression. It is then fastened into the wooden back or rim of the piano by being glued rigidly along its outer edges so that it remains permanently in a "live" condition, ready to vibrate. But it is also necessary to take into account the fact that the piano sound-board is covered by an iron plate, which bears the strain of the stretched strings. If we examine the iron plate and sound-board of a piano after stringing, we shall see that the entire structure thus formed, as well as the wooden back or rim, is in a condition partly of compression and partly of tension. Hence the whole structure has its own regular period of vibration and its own proper tone.

The object of sound-board design therefore must be to take advantage of the proper vibration of the board, plate and back together, and to see that the relative importance of each element is retained, without any one becoming unduly prominent. The fact is, of course, that the iron plate and the wooden back or rim exert a constant modifying influence on the vibratory activity of the board. In short, the various materials of which the back-structure (board, plate and back or rim) are made, all exert their individual influences, so that the ultimate vibratory period and composition of the wave form proper to the sound-board arises out of all these forces compounded. Hence the question of the dimensions and design of each of these elements is almost equally important.

I have made this digression because it is important to understand the reasons for differences in sound-quality as between various pianos. A detailed discussion of the design of these elements is the province of a technical treatise on piano construction.[1] The following remarks are appended, however, treating generally of the influence of the parts mentioned.

Influence of the Iron Plate. The cast iron of the plate is of course considerably stiffer and more rigid than wood. Its weight-for-bulk is also much greater; or, in other words, its specific gravity is

[1] Cf. "Acoustic Design."

represented by a higher index. Now it is well known that the vibratory form of any body which is enough under tension to induce susceptibility to vibrative influences is modified by the factors of density and rigidity. On the whole, any increase in density and rigidity tends to produce a wave form in which the higher partials are undamped. The more "yielding" structure of wood, as it were, has a damping effect on the less powerful partials, or rather, perhaps, is incapable of so elaborate a subdivision under the influence of the string vibrations. Hence the wood of the sound-board, if left to itself, will act as a damper on all the feebler partials of the strings, however many may have been left after the rebound of the hammer. The tone quality, therefore, will be founded on a partial-tone series scarcely extending above the eighth, with perhaps a trace of the multiples of the even numbered partials. Iron, however, modifies this procession by taking up the higher partial vibrations of the strings and reproducing them in amplified form. This is the most plausible explanation of the plate's activities, for it is certain that the more iron we have in close touch with the strings, at the extremities and on the bearings thereof, as well as around the sound-board area, the harder and more "metallic" is the tone; which of course means the existence in the tonal complex of high dissonant partials. Thus it is plain that

the iron plate should be designed so as not to overload the structure, and especially so as not to usurp all the functions of bearing. Wooden upper-bearing bridges are often useful in a piano which otherwise would produce a harsh and metallic tone. Excessive bracing or barring and undue massiveness are also bad features. In fact, we may say that the plate should be as light as possible; the lighter the better, so long as it is strong enough to stand the string stresses. This, of course, greatly depends on the precise tensions at which the strings are stretched, which again depends on the dimensions of the strings.[1]

Influence of the Back or Rim. The technical impossibility of producing an iron plate of the ordinary thin-sheet type, strong enough to bear the entire strain of sound-board and strings, without at the same time being too enormously heavy, has necessitated the use of a very massive wooden back for the upright piano, or a very stiff plywood rim for the grand. The back of the upright, of which I have already given some description, is extremely large and clumsy, and necessarily so. Its effect on tone can only be described as deadening; for there is no doubt that the natural vibrations of sound-board and plate are very much damped by the drag of the back.

[1] See *infra*, "String Dimensions," et seq., in the present chapter, and in general the parallel detailed discussion in "Acoustic Design."

Dimensions of the Sound-Board. The sound-board is limited, of course, according to the size of the piano, and therefore no particular rules can be given for its length and breadth, or even for its shape. It is observed, however, that the size of the piano and the tension and other features of the scale will require parallel modifications in the size and thickness of the board; that is in the vibrating area. But this is a matter which, in the nature of the case, must be determined by experiment. The point is that the board must be free to vibrate, in the particular situation created by the other conditions of the piano. If it is too heavy it will vibrate feebly on light playing, whilst with heavy playing its vibratory form will incline to be too much in its own proper period, thus smothering the resultant vibrations selected by the strings. If it is too light it will respond in light playing too readily and so again its proper vibration will intrude, while on heavy playing it will be unable to respond strongly enough to provide sufficient support to the strings. Thus the thickness must be graduated to the size. In practice piano makers have found it well to vary the thickness of the board between its two extremities. Thicknesses running from ⅜″ in the treble to a ¼″ in the bass are usual. But these are experimental matters and are determined always experimentally.

Ribbing. The sound-board must be ribbed in

order both to facilitate the transmission of vibration across the grain of the wood and to enable the structure to resist the various strains put upon it. These strains are (1) the down bearing of the strings; (2) the tension of the strings; (3) the opposed tension and compression of upper and under surfaces due to the crowning. The crown is necessary in order to give a proper bearing to the strings and also to resist their downward pressure.

The ribs are planed into curved surfaces where they are glued on to the board, so as to produce the "crown," which also is further promoted by planing the "linings," as they are called, of the back or rim. It is customary to use from 8 to 12 ribs, and these should be placed roughly at right angles to the run of the grain in the wood.[1]

Bridges. The position and curvature of the bridges are entirely governed by the string design. No special descriptions therefore need be given here, except to remark that the pins, which are driven into the bridge to give side-bearing to the strings, represent a survival from past days, in fact, from the days of the harpsichord. It would be mechanically better perhaps to use agraffes, or drilled metal studs, such as are found on the upper bearing bars of grand pianos (and in some uprights also).

[1] For a general discussion of these points cf. "Acoustic Design.

The bridges must be high enough to give a good down bearing and wide enough for a good side bearing. They should never be cut to permit the treble brace on the plate to pass through, but the plate design should be modified accordingly. A cut treble bridge always means a bridge that does not transmit the string vibration properly to the bridge, and invariably involves bad tone, and rapid break-down. A fatal obstacle to the conservation of piano tone is the degeneration of the board under string pressure; a process promoted by a cut bridge. A cut bridge means a bad piano.

Bridges should not be brought too near the edges of the sound-board, lest the elasticity of the board in response to the vibrations transmitted by the strings be rendered valueless for those situated at the end of the bridges. In tight places, if the string length is to be preserved (as always it ought to be), an extension bridge may save the day. Bass bridges can usually be treated best on the extension system, as bass strings are nearly always too short anyhow.

These remarks will be principally useful to the reader of this book in making clear to him the cause of piano tone-production and the reasons for differences in tone quality between pianos of apparently equal grade. I shall now briefly consider the string-scale.

Functions of the String. The function of the strings is to originate the various wave-forms which the sound-board is to amplify. Each wave-form must first be created by the string vibration; and therefore the dimensions, weight and method of stringing are of the utmost importance.

String Dimensions. Elsewhere I have made a tolerably complete study of string dimensions,[1] and here, therefore, I may be brief. The proportion of pitch from octave to octave is as 1:2, but since strings have weight and weight increases the length, this proportion will not hold good in designing string lengths. Piano makers, attempting to compensate for the factors of weight and tension, have produced various scalings of string length ranging from the proportions 1:1.875 to 1:1.9375 for each octave. In other words, instead of doubling the string lengths at each octave, each string is made $1\frac{7}{8}$ or $1\frac{15}{16}$ as long as its octave above. Intermediate lengths should be worked out, one by one, in proportion. Practice dictates almost universally a length of 2 inches for the highest treble strings.

Gauges. It is very clumsy and altogether unpardonable to change the gauges of the wire used in a scale when putting on new strings, unless it is obvious that some fatal defect in tension proportion exists. Regularity of tension is a desidera-

[1] Cf. "Acoustic Design."

tum always aimed at, but not often attained; mainly through lack of inclination to calculate closely. But the tuner should very carefully follow the original gauge of wire when re-stringing, for it is usually to be taken for granted that the piano as strung represents the best gauging that could be devised, considering its scale. The wire sizes used in piano making range from No. 12 (diameter = 0.029″), down to No. 26 (diameter = 0.063″). The sizes from No. 23 to No. 26 are used only for core wire on the heaviest bass strings of large pianos. In determining what string sizes to use, piano makers should attempt to obtain an even pull for each string from end to end of the scale.

Striking Point. This is another matter not always considered with sufficient care. In a good piano the point at which its hammer touches each string is chosen scientifically, for there is no more important detail in piano design than this. I have already discussed this subject in an earlier chapter (Chapter II), but it may here be observed that the tone quality of a piano is very closely associated with the position of the hammers in relation to the strings. The tendency in modern pianos is to make the striking point excessively high. Of course, as we all should realize by now, the necessary tonal reinforcement of the short upper strings must be brought about by raising the striking

point. But this point also is treated elsewhere.[1] It is to be hoped that readers will realize that in these details and the care that is taken over them rests the difference between good and bad piano making.

Bass Strings. The use of steel, brass or copper winding for the purpose of overweighting strings artificially, so as to make up for necessary shortening of true length requirements, is as old as piano making, and older; nor has any special improvement been made in the last half century save as to closer winding and lessening of slippage. It is still far too much the fashion for piano makers merely to send to the string winders a pattern showing their string lengths, leaving the weight of the strings to chance, skill or tradition. In fact, of course, the weight of a covered bass string is just as important as the length of a treble string; for reasons which must now be apparent to every reader of this book. It is, therefore, most advisable to consider the question of weight, with its intimate relation to tension whenever considering the improvement of the tone of a piano by putting on new base strings.[2]

Copper vs. Steel. The greater specific gravity

[1] Again it is proper to say that the brief descriptions of these technical questions proper to the purposes and aims of this book may be supplemented by study of the detailed treatment to be found in "Acoustic Design."

[2] Consult, for complete discussion of these points, "Acoustic Design," and to some extent Chapter II of this book.

of copper makes a thinner wire available to produce a given weighting. Excessive bulk is to be avoided in bass string making. Of course, copper tarnishes and in moist climates gets covered with verdigris, perhaps more quickly than the tinned steel wire rusts. The question of choice depends always upon the desired weight, for there is no good reason to believe that copper is tonally superior or inferior to steel.

To sum matters up, it may be said that the following points are important in any consideration of a string scale.

1. Accurate proportioning of lengths, measured string by string.

2. Careful graduation of wire thickness to assure regularity of tension from one end of the scale to another.

3. Placement on the bridges with enough space for each string to vibrate freely.

4. Avoidance of the practice of grounding bridge extremities right on the edge of the sound-board.

5. Avoidance of too much iron on bearing bridges.

6. Accurate weighting of bass strings.

In setting down these facts about the string scale, I have purposely avoided going into complete details; partly because the vibrations of a piano string and the details of stringing have already been treated in this book, and partly be-

cause I have elsewhere also discussed them quite thoroughly.[1] From the tuner's viewpoint all other necessary information is to be found in preceding chapters. Practical details are discussed in the chapter on piano repairing.

[1] Cf. "Acoustic Design."

Chapter VIII

THE ACTION AND ITS REGULATION

The movement or "action" which translates the motion of the finger-impelled key of the piano to the hammer, has been developed within the past fifty years to a high state of perfection. Fundamental work was mainly done in Europe, where Erard established the principle of double repetition which distinguishes the modern grand piano, and Wornum devised the tape-check which makes the upright action efficient in repetition and reliable in attack. Although these revolutionary inventions date back about a century from the present time (1929) the enterprise of contemporary makers was unequal to any immediate recognition of their superiority, so that for a long time both grand and upright pianos were fitted with less efficient movements; until the example of the more courageous among them, especially in the United States, showed quite unmistakably the immense superiority of double repetition and the tape check. From that time onwards—that is to say during the last thirty-five years—the use of the modern grand and upright piano action has become universal throughout the world, while we

may say that, so far as concerns the United States and Canada, there is almost complete standardization of the two types. Our descriptions therefore may be considered as being of general application.

Technical Knowledge of Action Principles. Experience from twenty-five years' contact with piano tuners convinces me that a thorough acquaintance with the scientific and mechanical features of the piano action is uncommon amongst them, even in a most elementary sense. I am proposing, therefore, to carry out, in the present chapter, a careful mechanical analysis followed by an equally careful description of the modern forms and a general explanation of the methods of regulating these. The discussion will, I hope, be not only professionally useful, but the reverse of tedious.

Functions of the Action. The functions of the piano action may be described as follows: (1) to convey to the hammer a motion which shall carry it toward the string for the purpose of inflicting a blow thereon, (2) to trip the hammer immediately before its actual contact with the string, so that it shall instantly rebound without blocking the vibration, (3) to permit the repetition of the hammer blow without complete release of the key and (4) to damp the string vibration as soon as the key is released. The functions are, of course,

identical for all forms of piano action, whether horizontal or vertical.

It is obvious from what has been said, therefore, that the piano action may conveniently be considered as divided into the following main elements: (1) the hammer, (2) the escapement, (3) the key, and (4) the damper. All piano actions have possessed the first, third and fourth of these, and in almost all cases a more or less satisfactory mechanical solution of the second has been carried out. The method of arranging these elements now to be described was first successfully worked out by Erard in 1821 for the horizontal and by Wornum in 1826 for the vertical, piano. Let us now consider how these various elements are coordinated. I shall begin with the grand piano.

The Grand Action. Erard's principle is today universal in grand piano making, but the particular form in which it is generally carried out today was developed by Herz from Erard.[1] The illustration given herewith (No. 19), shows a modern grand piano action manufactured by Messrs. Wessell, Nickel & Gross of New York. The parts, arrangement of parts and method of regulation are quite typical of the very best American practice.

The terminology may be considered as correct

[1] Cf. "Acoustic Design" and *Encyclopædia Britannica* article "Pianoforte," 11th and later editions, and "History of the American Pianoforte," by Daniel Spillane.

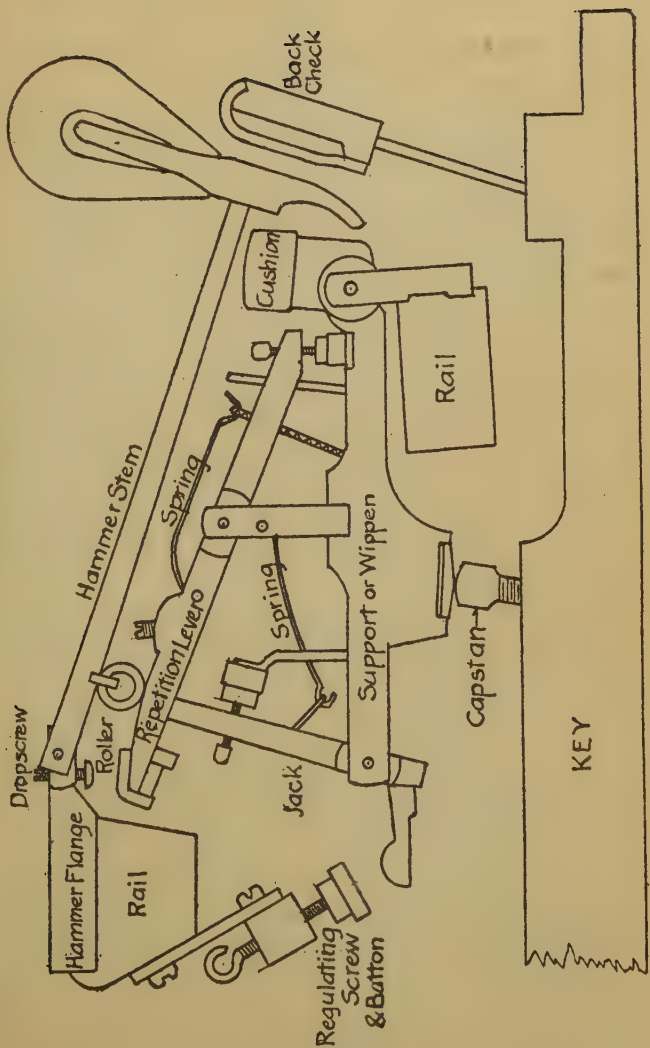
Back Check
Cushion
Rail
Hammer Stem
Spring
Spring
Support or Wippen
Capstan
KEY
Repetition Levero
Roller
Dropscrew
Jack
Hammer Flange
Rail
Regulating Screw & Button

FIGURE 19

and as following the practice of the best American action makers.

Operation of Grand Action. The student should now follow the argument by means of a working model, or by the simple process of removing the action from a grand piano and studying its motions. Pressing down slowly the front end of the key we observe that the rise of its rear end affects the capstan, which lifts the wippen, on which are pivoted the repetition lever and the jack. By lifting the hammer stem up and away from its cushion it will be seen that the top of the jack works in a groove in the repetition lever. Moreover, the upper surface of the repetition lever bears against the roller under the hammer stem, the weight of which and of the hammer, depresses the repetition lever until the jack is also in contact with the roller. When, however, the key is depressed we note that the lifting is first done by the repetition lever, and that the jack comes into play only after the former has begun to lift the hammer. As the key is farther depressed, the jack lifts on the hammer and pushes it up to the string until it is tripped by its lower end coming in contact with the regulating screw and button. The momentum of the hammer carries it the rest of the way to the string, whence it immediately rebounds and is caught by the back check which holds it until the key is released by the finger, when the hammer

again is supported by the repetition lever, which holds it up while the jack slips back under the hammer-stem roller. The function, then, of the repetition lever is seen to be that of assisting repetition, as the name implies. By its means the hammer may again and again be operated through the jack without the fingers being obliged entirely to quit the keys, as may be seen by practical test on the action. So long as the repetition lever holds up the hammer, by means of the expansive strength of its spring, just enough to enable the jack to slip back into place under the roller, the stroke may be repeated; and therefore it is plain that the key need be lifted only enough to afford the finger a secure stroke. Really, then, the repetition lever is this in fact as well as in name and through its agency the escapement which otherwise would have to be affected by quitting the key and giving it time to rise entirely, is effectually performed.

Comparison with Square Action. The old square piano presents in its action an interesting comparison with the above. Here will be seen the difference between single and double repetition. In the square action, the repetition lever is omitted and the jack can only find its way under the hammer butt safely, when the key is allowed to rise almost to its full height in front. Thus the finger action must be higher and the execution of rapid passages becomes difficult, if not impossible.

The Back-Check. There is, however, one other extremely important element which so far has only incidentally been mentioned. This element is common to all types of piano action, grand square and upright alike, and is found in even the earliest successful pianos. I refer to the back-check. The object of this is to catch and hold the hammer firmly on its rebound, thus assisting the recovery of the jack and the repetition lever. Even in pianos like the square, or older makes of grand, one always finds the back-check, whether the double-repetition device be present or not. Indeed, the inventor of the pianoforte action, Cristofori, to whom belong premier honors as the father of piano making, certainly mastered the necessity for the back-check in the course of his experiments, for he devised them in almost modern shape, and built them into his last pianos. This may be seen by examining the Cristofori piano now standing in the Metropolitan Museum of Art, New York, the date of which is 1720. The back-check, then, is as old as the piano. This fact alone shows its essential value, for not otherwise would the necessity for something like it have been so quickly discerned. Cristofori, of course, was an uncommon genius, for in his last actions (1720 and later) he had also an under-lever, not unlike the repetition-lever of the modern grand piano, and very much like the under-lever of the "Old English Square Action" so-called; the object

whereof is to steady the hammer and impart elasticity to the blow.

It will be observed that the back-check comes into action when the hammer, rebounding from the strings, is descending towards a position of rest. The spring of the repetition-lever would naturally throw the hammer back towards the strings again, and thus keep it dancing up and down instead of bringing it sharply to rest. Of course, the back-check is to be carefully adjusted so as to catch the hammer at just the right point in its arc of travel. Thus, the back-check performs two functions, (1) it catches and holds the hammer on its rebound, where the repetition-lever alone could not hold it and (2) it allows the repetition-lever to lift the hammer again the moment the key is released. In other words, since the back-check works from the key direct, it follows that the least raising of the back end of the key releases the check from the hammer, whereupon the repetition-lever does the rest, as described above; but the check is necessary to prepare the hammer for the action of the lever. The operating or sound producing part of the grand piano action may then be described by saying that the key moves the repetition-lever, the lever moves the hammer and then lets the jack move it farther, the jack moves the hammer to the string and then trips it, the check catches the hammer on rebound, and the lever lifts it the moment

the key is released; whereupon the cycle of motions may once more be set going, to be repeated as often as the key rises at the back enough to ease the back-check from the hammer head.

Turning Points. Thus the grand action appears, in its sound producing parts, as comprising six centers and six radii, describing six arcs of turning. All piano actions may be similarly considered.

The Damper Action. The function of the damper is to rest on the strings when the key is not in use and so prevent any vibration of the string, especially to prevent any sympathetic vibration which might be produced by the vibration of another string having partials in common. As will at once be observed, however, the damper is so positioned that when the key is in motion, and has descended about one-third of its total dip, the damper lever begins to lift and with it also the damper head, so that by the time the hammer is about to make its stroke, the damper is well clear of the string. Upon the return of the key to its position of rest, the damper is allowed to fall back on the string, being pressed down thereupon by means of the spring in the damper lever.

Damper Pedal. The damper action can be entirely raised from the strings, independent of the operation of the piano action, by means of the damper rod (not shown in illustration), which runs

underneath the line of damper levers and is controlled by the right hand pedal of the piano through suitable trap-work usually placed under the key-bed.

General Construction Practice. The piano action in all forms is a wooden machine. Numerous attempts to devise a satisfactory action of metal have so far been uniformly failures, largely because the peculiar requirements of lightness, independence of lubricants and low frictional resistance seem to present insuperable difficulties. Although, therefore, the stickiness, dampness and liability to warping which naturally characterize wooden machinery of any sort render the piano action somewhat unreliable and distinctly troublesome at times, it is not likely that much change will be made in the future, unless indeed some entirely new principle is discovered. On the whole, however, the wooden piano action, especially in its grand piano form, is a wonderfully efficient piece of machinery.

Being in effect a series of centers, with radii therefrom moving through arcs of circles, the piano action requires numerous pivotal points. These are now universally provided by means of flanges carrying brass center-pins, working in bushed holes, on which the levers turn. These flanges have been always of wood hitherto, but during recent years there has been a drift towards

brass or other metal forms which are more rigid, less likely to loosen at the bushings, and more easily adjusted.

The woods used in the piano action have been briefly mentioned already,[1] and here it may principally be said that the practice of the best makers has not noticeably varied during many years. Hard woods such as maple, ash, and sometimes oak, are used where strength and rigidity are the requirements, as for instance in hammer butts, hammer shanks and supporting rails. Key-frames are usually of white pine and keys themselves of the same wood, particularly chosen for straight grain.

The key-frame and key-board are today just as they were a century and more ago, at least as to essentials. No particular progress has been made, except that we have better felt, larger pins for front and balance rails and accurately machined mortises and holes. But otherwise there is nothing of importance to record.

The felts used in piano actions are especially manufactured for the purpose, the principal varieties being the very fine close-textured red-cloth used for bushing and the spongy green and white material used for punchings. Cardboard and paper punchings are also used for fine work under the keys, as described later.

[1] Cf. Chapter VI.

The brass or german silver center-pin is universal. Attempts to substitute other devices have not succeeded. What is true of pins in this respect is even more true of the springs, which are always made of brass, but which, in grand pianos especially, seem to collapse and lose their "life" very soon under modern conditions. It would probably be a good thing if experiments looking to the substitution of steel springs were made; but the trade is conservative here, as everywhere. Capstan screws are also of brass always, but the remaining hardware is either cast-iron (action frames, screws, etc.), or steel (damper rods, etc.).

Detail Variations. Older grand pianos are often found (if made prior to about 1890) to have wooden rockers with short extension rods of wood, in place of the capstan screws. The device is not admirable, mainly because it renders the action less accessible.

Wooden action frames were also common in the old days, and wooden action rails are still almost universally used, although modern makers are beginning to see the advantage of at least supporting these rails by metal bars.

The construction of the repetition lever and of the wippen in general is subject to considerable variation of practice. Some makers use a single spring, with double or single bearing. Sometimes the travel of the jack is limited by a metal spoon,

as shown in Figure 19, and sometimes by a wooden post, while in some actions no adjustable means are considered necessary. The greater number of modern grand piano actions are provided with tensioning screws whereby the strength of the wippen springs may be adjusted more surely than would be possible by any method of bending. But older actions are usually without this adjustment.

Steinway grand pianos are distinguished by the use of an octagon head screw in place of a capstan screw, which necessitates the use of a special wrench for turning them. The same makers use metal sheathing for their action rails, which are of special design.

The cushion on the wippen, above which the hammer is normally held, has given way in some grand actions to a fixed, independently supported hammer-rail on which the shanks rest as they do in an upright.

Soft Pedal. These last, however, are made specially for the purpose of substituting a lift of the hammer-line by the soft pedal for the usual shift of the key-board.

Sostenuto Pedal. On most modern grand pianos, each damper-lever is provided with a tongue of felt projecting from it. In front of the line of tongues is a brass flanged rail which can be rotated by depressing the middle pedal pro-

vided for the purpose. After a key or keys has been struck and their dampers raised, the pedal may be depressed before releasing the keys, and the flanged rail then turns, catching the felt tongues and holding up the dampers. The keys may then be quitted. This device is useful in getting tone-color and adds to the tonal resources of the piano most markedly.[1]

Regulation of Grand Action. The processes which together constitute the adjustment or "regulation" of the grand piano action are not complicated when studied systematically and in order. To describe them is by no means difficult; and indeed the only difficulty is to get enough practice to be able readily and rapidly to perform the various processes. In order to simplify the explanations as much as possible, I shall simply detail in order the various steps taken in regulating the action of the grand piano, so that the reader may be able to see what is done and why. A first necessity, however, is some consideration of the question of action "touch" considered from the viewpoint of the pianist.

"Touch." It is important that the pianist should have a piano with an even "feel" to the keys, uniform depth of touch and uniform resistance, so far as possible. The practice of makers in this re-

[1] Many other small detail variations may be found amongst the work of individual makers, but for general remarks along these lines see Chapter X.

spect has greatly varied since the birth of the piano, but curiously enough the most modern ideas in regard to depth and resistance are again virtually the same as those of one hundred years ago, having descended from the excessive heights attained in the middle nineteenth century, when piano makers vainly attempted to make pianos large, heavy and loud enough to suit the piano-thumping school of musicians now happily out of fashion.

Depth of Touch. The pianist considers depth of touch from the standpoint of convenience. He wants the touch to be deep enough to give him a good "feel," and shallow enough to permit of rapid passage work. General practice now accords the key a touch-depth (dip of the front end) of ⅜ inch. The bass end may be a little deeper, but on the whole this is not essential.

Touch-depth, however, the piano maker must consider in connection with the rise of the rear lever of the key. Moreover, it naturally follows that as the front dip is to the rear rise, so is the length of the front lever (front-rail pin to balance pin) to the length of the rear lever (balance pin to capstan). If therefore the requirements of any section are such that special height of rise is required, the position of the balance pin must be shifted accordingly. Usually, however, a rise of ¼ inch for the back is found sufficient. Taking

this as a basis, the following simple calculation gives the other proportion:

Depth of front dip $\frac{3}{8}$ inch.

Height of back rise $\frac{1}{4}$ inch.

Front Lever : Back Lever = Front Dip : Back Rise.

But, $\frac{3}{8} : \frac{1}{4} = 3 : 2$.

$\therefore$ Front Lever : Back Lever = 3 : 2.

If, however, the proportions between dip and rise are altered, so also the length proportions between front and back levers are affected.

Length of Keys. In grand pianos of domestic size the key lengths have finally been settled at about $15\frac{3}{4}$ inches from front rail pin to capstan. Shorter grands of course have to carry a smaller key and concert grands a longer one. In these cases, the proportionate lengths must still be as above, for if any change is made on the mistaken idea that some fixed length instead of a fixed proportion is to be followed, the entire key proportion will fall to the ground and the touch will undoubtedly be bad. By retaining the proper proportions as indicated above, the short key will be effectual enough, although it must be remembered that the shorter the key the less the leverage for an equal touch depth.

Resistance. The practice of the best makers has finally settled the resistance or touch weight at $2\frac{1}{2}$ ounces approximately. Some variation be-

tween the extreme bass and treble ends is permissible and desirable. In fact it would be well to consider a resistance in the extreme bass of 2¾ ounces, graduated to 2½ ounces in the middle and to 2¼ ounces in the extreme treble. Changes in resistance may be made by drilling the body-wood of the keys and putting in small round pieces of lead where required. The piano maker should always carefully ascertain the weight required to depress each key when the action is in contact with it and having done this adjust accordingly by putting lead in the backs of the keys to increase the resistance, or in front to lessen it.

Order of Regulating. Following the general factory practice we may consider the regulation of the grand piano action in the following order:[1]

1. Key-frame and keys. Key-shift and soft pedal.
2. Action.
3. Dampers, damper pedal and sostenuto pedal.

Keys and Key-Frame. 1. Keys are removed from frame, which then is fitted with felt punchings for front and balance rails, and strip of cloth for back-rail.

2. Keys are replaced and eased off, by being tested for clearance on front and balance rails. When lifted each key should fall back naturally

[1] For the sake of clearness, it will be necessary to include certain processes actually classified as part of the preliminary action-finishing.

and readily, but not loosely. Key-pliers are used for squeezing the bushings wider when needed. If keys are too loose, bushings may be squeezed together by punching with a wooden punch.

3. Key-frame is then placed under action (having been previously roughly adjusted in finishing room when capstans were placed in each key) and general level of key-frame in relation to action is noted.

4. Action being removed again, a piece of lead is placed at rear of each key, of weight sufficient to counterbalance resistance of action. This holds keys up in front and down in rear. Keys are then carefully straightened by knocking over balance-rail pins slightly when needed, then spaced by bending front rail pin where needed, and lastly leveled. This latter operation is performed by putting under extreme treble and bass keys, over front-rail pin, wooden block measured exactly equal to calculated depth of dip. Straightedge is then put over keys on line immediately above blocks and general level of keys is adjusted up to the extremes. If too high, key-frame may be planed off where balanced rail is screwed in, or if too low, balance-rail may be "built up" by putting strips of cardboard between it and bottom of key-frame, in same places.

4. Key-frame is then replaced in piano with keys taken out where soft pedal shifting lever

touches frame. This lever is closely adjusted so that the key-frame moves as soon as pressure is put on pedal. Points of contact are black-leaded with powdered black-lead and burnished with heated steel bar. The spring which retracts the key-frame is also tested and adjusted if necessary.

5. Action being replaced on keys, hammers are adjusted so that length of stroke is not more than 2 inches from end to end. (This is the action-finisher's work originally and the regulator merely looks it over.) Each hammer must then be adjusted to rest over its cushion about 5/32 inch. Capstans are adjusted accordingly and care taken to see that the hammers are level.

6. Jacks are then adjusted so that hammer trips up at about 5/32 inch from the string (here practice varies but close regulation is desirable). This is done by turning regulating button of jack.

7. Jack is regulated by turning button and screw on repetition lever so that jack normally rests in middle of groove in repetition lever. Usually a line on groove is marked to show right place.

8. Back-checks are regulated so that (1) they stand even and straight in line, (2) catch the hammers firmly without any slippage even on hard blows and (3) catch hammers when same have descended on rebound about 1/8 inch from the strings. Only a proper bending iron or bending pliers should be used for this work.

9. Repetition lever is regulated; (1) spring is made strong enough to cause the hammer to dance a little and lift slightly when back-check is released. Most modern actions have screw-tension adjustment, but otherwise tension may be changed by bending wires with hook; (2) rear of lever is set low enough to permit plenty of space between it and its travel-limiting hook, so that the jack may rest about $\frac{1}{64}$ inch below the level of the grooved end. This is usually done by means of the regulating button (Figure 19); (3) height of rise of repetition lever under hammer-knuckle is regulated by the screw which is seen in Figure 19 under the right hand end of the repetition lever, so that rise of lever is stopped when hammer is still about $\frac{5}{32}$ inch from the string, or (what is nearly the same in practice), a little before the jacks trip off; just enough before to give the jacks about $\frac{1}{8}$ inch lift by themselves before tripping.

After-Touch. 10. Action and keys being in piano, keys are tested for evenness of dip. This is best done by means of wooden block of proper depth whereby each key may be tested from extreme bass up, by placing block on top of key and then depressing. If block sticks up too high the regulator takes out punchings underneath front; if block sinks below level of key-top he puts more punchings underneath. Paper punchings are used for this work.

11. Testing for after-touch is then done. After-touch is the slight lifting of hammers which should take place when keys are gently released. If the adjustment is correct, the release of the key immediately releases the back-check and the repetition lever lifts the hammer slightly. To make after-touch right, the regulator puts enough punchings under the key to make sure that the hammers will not release from the back-checks except under a very hard stroke; and then takes out from this about $\frac{1}{32}$ inch punching depth. This will leave the necessary after-touch.[1]

Dampers and Pedal Work. 12. Dampers must lie square on the strings and their wires must work freely in the bushings.

13. Each damper lever must be regulated so that the whole line of dampers, when lifted by the sustaining pedal, rises evenly and as one.

14. Damper wires must be regulated so that the lift of dampers does not exceed $\frac{1}{4}$ inch in bass and a little less in treble.

15. Damper lever line is to rest above rear of keys at such a distance that key has performed about $\frac{1}{3}$ of its dip before dampers lift.

16. Damper lift-rail or rod operated by sustaining pedal is to rest closely in contact with damper levers.

[1] It is often necessary and always better to regulate the black keys separately and with the white keys removed.

17. Sustaining pedal trap-work is to be regulated to eliminate nearly all lost motion, leaving just a suspicion for the greater ease of the foot work.

18. Sostenuto pedal work is to be regulated so that the felt tongues on the damper levers are level and are free of the flanged rail until it is turned, when they are caught by it if the keys belonging to them have been depressed and held down.

This is an outline—not entirely perfect, for this would not be possible in a book—of the process of regulating grand actions. I now pass to considering the action of the upright piano.

The Upright Action. Familiar to most of us as the upright piano undoubtedly is, one can only wonder that the stock of public information about its action is so generally inadequate. Even professional tuners are by no means always guiltless of ignorance in this respect, so that the real meaning and inner refinement of the upright action are almost as much a closed book to many of them as anything else one could mention. Crude and rule-of-thumb methods of regulating and repairing, handed down by tradition and practiced by men themselves unable to appreciate the piano from the performer's standpoint, are calculated to improve neither the durability of the piano nor the reputation of the tuners. It is therefore with-

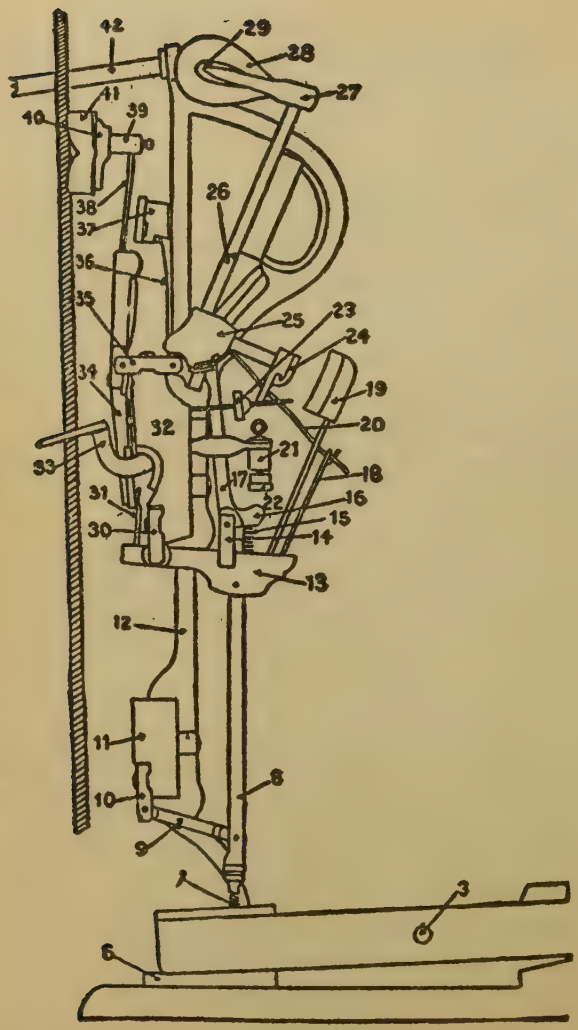
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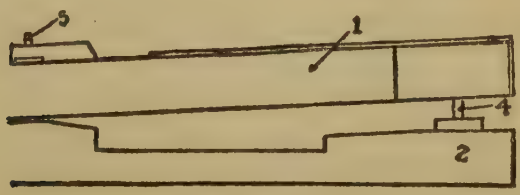
FIGURE 20

1. Key.
2. Key-frame.
3. Key lead.
4. Front rail pin and punching.
5. Balance rail pin and punching.
6. Back rail cloth.
7. Capstan screw.
8. Abstract.
9. Abstract lever.
10. Abstract lever flange.
11. Lower action rail.
12. Action bracket.
13. Wippen.
14. Jack flange.
15. Jack spring.
16. Jack knuckle.
17. Jack.
18. Bridle wire.
19. Back check.
20. Bridle tape.
21. Regulating rail.
22. Regulating button and screw.
23. Jack stop rail.
24. Back stop.
25. Hammer butt.
26. Hammer shank.
27. Hammer molding.
28. Hammer top-felt.
29. Hammer under-felt.
30. Wippen flange.
31. Spoon.
32. Middle action-rail.
33. Damper lifting rod.
34. Damper lever.
35. Hammer and damper flange.
36. Spring rail spring.
37. Spring rail.
38. Damper wire.
39. Damper block.
40. Damper head.
41. Damper felt.
42. Action bolt.



out any further apology that I devote space to an analysis of the upright movement as painstaking as that which we have just finished.

Figure 20 shows the modern upright action, to which is appended a complete terminology.

Distinctive Features of Upright Action. The upright piano action is in two parts, detached from each other and only in mechanical contact; namely the keyboard and the action proper. These two can therefore be handled separately in a convenient manner. The hammer does not fall back by gravity, and so must be assisted by the provision of an entirely new element, the bridle-tape (No. 20), as well as by the hammer spring (No. 36).

The hammer-line rests against a hammer-rail and the soft-pedal operates by swinging this rail to bring the hammers nearer to the strings. This creates lost motion between capstan and abstract, which in some actions is taken up by special devices.

There is no special repetition lever.

Operation of Upright Action. The key being depressed at its front end, the rear end rises, lifting the abstract (8) and the wippen (13). The rise of the wippen lifts the jack (17) which swings the hammer butt (25) carrying the hammer, until tripped at its knuckle by the button (22). Tripping of the jack throws it out of contact with the

hammer, which moves forward to the string by its own momentum, and rebounds, assisted by the spring, till it is caught and held by the back-check (19) working against the back-stop (24). When the key is released, the hammer is pulled back by the tape, which also assists in the retraction of the jack. This latter important part of the process is further assisted by the peculiar shape of the leather-covered hammer-knuckle against which the jack bears. When the key has already risen high enough to bring the parts here described into play and to start them on their arcs of turning, the spoon (31) presses against the damper lever (34) and the damper is pushed away from the spring. When the key is released, the damper is retracted with it until it again presses against, and damps, the string.

The action of the upright is somewhat simpler than that of the grand and the absence of a repetition lever is felt in the higher finger action it demands and in its less delicate repetition. Nevertheless, if properly regulated, this action is efficient and rapid.

Comparison of the Upright with the Grand Action. The characteristic feature of the upright action is the bridle tape. The value of this tape lies mainly in the slight extra pull it manages to impart to the hammer butt when the hammer rebounds from the string, and after the back-check

has caught the hammer and has been released by the release of the key.

The tape would not have any special value but for the fact that the hammer, having been caught by the back-check, naturally would hang a little after its release, if it did not receive the gentle pull caused by the fall of the wippen with which the bridle tape connects it.

The tape is, in fact, to the upright action what the repetition lever is to the grand. Until these two features had been devised and applied to their corresponding actions, the piano was an extremely imperfect instrument. The modern upright piano owes its present touch effect to the tape, just as the touch delicacy of the grand is due to the repetition lever. Of course, the grand action is the more delicate and responsive of the two, for it possesses the double repetition. This the upright cannot have, not to mention the fact that the fall of the hammer through gravity is of course far more effective than its retraction by springs. The upright action blocks more easily than does the grand, and finger movement must be higher to secure repetition.

Detail Variations. The metal flange is used more frequently on the upright than on the grand action. The first step in this direction was taken years ago when the continuous brass plate with flanges, carrying each section of the hammers on

one plate, was brought out. This did not prove to be the required solution, but the individual brass flange has since come forward and appears to be perfectly satisfactory. Certainly it does make the action more rigid and durable.

Metal rails or metal reinforcements to wooden rails have also come into use and constitute likewise an admirable improvement.

Some actions are provided with an extra spring in the jack, called a repetition spring. Others are shorn of the ordinary spring rail, in place of which is a separate support for each spring in the back of the hammer butt, fastened to a loop cord secured in the flange.

Lost motion attachments are common. These consist of a mechanical movement whereby the rise of the hammer-rail, on the depression of the soft pedal, causes a proportionate lengthening of the abstract, to fill up the gap which would otherwise be left between capstan and abstract.

Many attempts have been made at various times to eliminate the tape and provide for reliable repetition by other methods. One principal objection to the tape is its liability to destruction by mice or other domestic pests. Other upright actions often have props fixed in the keys instead of the more modern abstract. These are adjusted by turning the wooden button up or down on its wire.

Pedal Actions. The soft pedal of the upright

piano merely swings the hammer-rail in an arc so as to bring the hammers nearer the strings.

The damper pedal operates through a damper-lifting rod (33) whereby the bottoms of the damper levers are thrown forward, tilting back the dampers from the strings.

A third pedal is usually found. Sometimes this operates to draw down a rail from which depends a strip of thick felt, so as to interpose the felt between hammers and strings and so muffle the tone. This is called a "muffler" pedal. Another form is an auxiliary damper action, operating on the bass dampers only, while still another kind is an adaptation to the upright of the grand sostenuto pedal. A fourth and last is a mere duplicate of the soft pedal.

Materials. All that has been said on this subject in the sections relating to grand actions is applicable to the upright, and I shall therefore content myself with referring the reader to them, suggesting also that he study the various representative actions he encounters, for the purpose of discovering at first hand the practical facts of material and constructional usage as displayed by manufacturers. In this case, as in all others, practical first-hand knowledge is priceless.

Regulation of Upright Action. Certain parts of the work of regulation are identical in method with what we have already learned concerning the simi-

lar processes in the grand action, but the differences in design between the two bring about such differences in parts and functions of parts that a separate description is necessary everywhere save in one or two instances; as will now be seen.

1. *Keys.* The preliminary work of felting, easing, leveling, and spacing keys is done just as before described in the sections on the grand action. This work, in the present case, may be done without removing the action from the keys, so that it is unnecessary to put lead pieces at the backs of the keys to hold them up.

2. *Hammer-Blow.* This is regulated to be about 1 9/10 inches. Regulation is made by putting felt cushion between hammer-rail and action brackets.

3. *Lost Motion.* Lost motion between capstans and abstracts is taken up. Correct adjustment is indicated when the hammers lie freely on the hammer-rail, neither forced above it nor with a gap in the action below them. As long as the back-checks move without moving the hammers, there is lost motion; but it is advisable to leave a little, a very little, play, so that the jack is not tight up against the hammer knuckle.

4. *Back-Checks.* Back-checks are straightened by means of the back-check bender or a pair of bending pliers, so that each check lies squarely in front of its corresponding stop.

5. Back-checks are lined up so that each check catches its back stop when the hammer has descended about one-third of its total drop on the rebound.

6. *Let-Off.* Jacks are adjusted for the trip of the hammers, which is done by turning regulating screws, using a regulating screw driver. Hammers should trip at a distance of from ½″ (bass end) to ⅛″ (treble end) from the strings.

7. *Bridle-Tapes.* Bridle-tapes are adjusted to lift wippens evenly and all together. This is tested by hammer-rail up and down, so that bridle-tapes lift and drop accordingly. Adjustment is made on bridle-wires.

8. Bridle-wires are adjusted so that they do not knock against back-check wires and lie straight and square.

9. *Dampers.* Dampers are adjusted so that they lie square against strings.

10. Rise of dampers is adjusted by moving damper-rod back and forth, which shows whether all dampers begin to move together. Adjustment is made by bending spoons. Dampers should lift not more than about ¼ inch from the strings and their movement should begin when key is about one-third of the way down.

11. *Sustaining Pedal.* The sustaining pedal action is adjusted to lift the damper-rod promptly. Adjustment is made on the trap-work at the bot-

tom of the piano or between top of pedal rod and damper rod.

12. *Soft Pedal.* Adjustment is made at hammer-rail.

13. *Middle Pedal.* See *supra* in reference to grand actions.

14. *Touch.* All instructions regarding laying of touch in the grand action apply here to the upright.

The foregoing descriptions are sufficient for the purposes of this book. It has been my intention mainly to give the reader a good working knowledge of the grand and upright piano actions in the light of their functions. Purposely I have given most space to the grand action because that one is least understood; while everything said about its principles can at once be applied to the upright. The upright action is a series of turning points, just as is the other.

The upright has almost the same parts and the same adjustment. But uprights are more familiar and hence better understood.

Regulating Tools. It is impossible to do any good work in piano action regulating without appropriate tools. The most important of these, with which the student should not fail to provide himself, are:

Long and short narrow-blade screw drivers

Very thin screw driver, for grand actions

Regulating screw driver
Key pliers
Bending pliers
Small regulating screw driver for grand actions
Key spacer
Damper bending iron
Spring adjusting hook
Spoon bending iron
Parallel pliers
Capstan screw iron
Hexagonal wrench for Steinway actions.

Professional regulators, who operate in piano factories, use, of course, a much wider selection of tools, often including many devised by their own ingenuity. But the traveling tuner need not carry an arsenal of tools with him, nor indeed burden himself with one single not actually indispensable piece. The selection suggested above may at first seem to be formidable in quantity, but really it represents an irreducible minimum, below which the judicious worker cannot, and will not, go.

CHAPTER IX

THE HAMMER AND ITS RELATION TO TONE

The hammer is the "characteristic" of the piano; its sign and symbol. It was exactly the invention of the hammer, and of a movement to connect it with the key, that made the harpsichord into the pianoforte. The object of the labors which led Cristofori to his epochal application of a principle until then regarded as practically unrealizable, was tonal gradation. He sought a keyed stringed instrument of music susceptible to dynamic control through variations in the stroke of the fingers upon its digitals. He was looking for something better than the light thin tinkle which represents the ultimate achievement of any harpsichord, no matter how beautifully made. No increase in the vigor with which the harpsichord key is depressed will do more than gently pluck the string. Thin, rippling, tinkly, the tone of the harpsichord and of its kindred claviers could not always suffice for the full satisfaction of musical art. True, the harpsichord persisted for nearly a hundred years after Cristofori began his work in the little shop among the outbuildings of the Medici Palace at Florence; but on the day he pro-

duced his martello[1] and the movement which connected it with the key, not only was the piano born, but the harpsichord was doomed. Henceforward, percussion instead of plectral vibration was to be the characteristic of keyed stringed instruments.

The two hundred years that have elapsed have brought no change in principle, although they have seen much improvement in detail. The piano hammer remains precisely what it was. Changes in the materials of which it is made and improvements in the manner of its manufacture have been produced as part of a gradual general refinement of our conceptions of the piano and of its true place. These conceptions have brought about improvements in manufacture, which have been accompanied by parallel improvements in the machinery of manufacture. But the principle remains today what it was two hundred years ago.

Function of the Hammer. Fundamentally, the piano hammer consists of a rounded cushion of some flexible resilient material mounted on a wooden molding and provided with a right angle stem, the other end of which is connected with the piano action. The object of the hammer is to excite the strings into vibration. We know that string excitation may be carried out in many different ways. When percussion is the method, two

[1] i. e., hammer.

elements immediately present themselves for consideration. The string may be struck with greater or less vigor, while also the manner in which the blow is delivered, as regards place on the string, nature of the material, and so on, may be varied so as to produce variations in the color of the tone. In short, the hammer not only may control the comparative strength of the emitted tone but also to a large extent its color.

Now we have already discussed at considerable length the influence on tonal character involved in choice of the point of contact of the hammer with the string. The reader will now wish to consider questions as to the material of the hammer, and the methods of treating this material so as to produce in each individual case the best possible tone. It will be advisable to consider the question of material and workmanship first.

Material. The first hammers were wedge-shaped wooden blocks covered with hard leather and topped with a soft skin, like that of the elk. In the time of Beethoven the covering material was still leather, although an oval shape had been developed. The felt covering which has long superseded all others was developed during the nineteenth century, principally through the work of manufacturers in the United States, where machines for covering the moldings were first successfully made and used. The present hammer

consists of a wooden molding of approximately oval shape, over which is stretched a strip of hard felt known as the under-felt.

This is glued in place and over it is fastened in the same way a thicker strip of softer felt called the top-felt. The two strips of felt are cut from large sheets, and glued on to the hammer moldings in one piece; the moldings themselves being also in one piece. Thus a whole set of hammer molding is turned out complete, and receives a strip of under-felt nearly as wide as the whole set of hammers, which in turn receives a strip of top-felt. The solid set is then taken out of the machines and sawed into separate hammers.

The sheets of felt are of different weights, running from 12 to 18 lbs. per sheet or even higher. Hammers are known as 12-lb., 14-lb., or 18-lb. hammers according to the weight of the sheet from which their top-felt is taken.

The sheets themselves are prepared in tapering form, so that the thickness runs from greater to less in a constant gradation from one end to the other. In this way is preserved the gradation of thickness in the hammer-felt from bass to treble of the piano. Bass strings, of course, require the heavy hammers and treble strings the light ones.

Felt. The peculiarities of hammer construction must be considered definitely if we wish to become acquainted with the reasons for the sometimes

peculiar behavior of hammers under usage. In the first place, it should be observed that felt is a very different thing from woven or spun fabric. Felt is the result of pressing together layers of wool in such a way that the fibres, which are serrated or jagged, fasten into each other and form a solid mass, which cannot be torn apart and which possesses in a high degree the qualities of flexibility and resiliency, together with strength and durability. At the same time, however, it must be remembered that felt is a material which is really at its worst when under tension; yet hammer-felt is continually in tension after the hammer is manufactured. The felt sheet is stretched over a wooden molding, with the result that the whole outer surface of the sheet is subjected to considerable tensional strain, which tends constantly to pull the fibres apart; fibres which have in effect merely been pressed together in the process of felting and which therefore may be pulled apart under stress.

This peculiarity of the felt hammer is seen in sharp relief when a piano has been used any length of time. But even before this, even in the factory, the processes of tone regulation invariably exposes this imperfection. In order to understand how this is so, however, we must see what that process is and how the condition of the felt affects tonal result.

Tonal Properties of the Hammer. Any tone-color can, of course, be expressed in terms of a definite wave-form. Now, all piano makers are agreed, generally speaking, upon the kinds of wire to be used, the points of contact, the employment of felt hammers and the general taste of the modern ear for piano tone; or rather for what we have come to accept as good tone for a piano. Experiment shows that a wave-form produced by the vibration of a strong fundamental with the following twelve partials in diminishing strength, excluding the ninth and eleventh, represents the kind of tone which is generally accepted as refined, pure and noble, throughout the middle and most characteristic region of the piano.

But the practical requirements of piano making render very difficult the attainment of a tone-quality which can be signified in a definitely graphic manner. The description attempted above is only provisional and is admittedly crude. It applies only to the middle regions of the piano. Below that region the wave-forms become more and more overloaded with partial tones. Above it they tend to become, more and more, pure sine curves, showing fundamental vibrations only, with few or no concomitant partials.

It is plain, of course, that the hammer enters the tone-producing systems as a very powerful factor. Its influence, however, is exerted in a narrow field.

Putting aside the question of contact points, which after all is a matter for the scale draftsman and not for the hammer-maker or the tuner, we find that the factors of hammer influence which we can control are three in number, namely: (1) the hardness or softness of the under-felt; (2) the hardness or softness of the top-felt and (3) the size and shape of the hammer. Let us consider these.

Under-Felt. The under-felt must always be relatively firm and hard, if only because the necessity exists of interposing an effective cushion between the hard wooden molding and the contact surface. It is equally clear that the function of the under-felt is, just as much, that of "backing up" the softer top-felt.

Top-Felt. The function of the top-felt is to inflict the blow on the string in such a way as to produce the necessary wave-form required. Now, it is plain that the softer the top-felt may be, the less quickly will it rebound from the surface of the struck string. A soft top-felt of course will have its fibres relatively more loosely interconnected on the top; a condition partly arising from the fact that the upper surface of the top-felt is stretched at high tension over the under-felt and molding. The cushion of soft fibres thus formed will tend to cling to the surface of the string a little longer than if it were perfectly smooth and hard. This clinging will have the effect of damp-

ing at least some of the high partials which originate around the point of contact of the string. When it is understood that the hammer, even when new, presents a relatively blunt surface to the string, this can easily be realized.

Soft and Hard Felt. It now becomes plain that:

1. The softer the top-felt the less complex will be the wave-form and the more mellow the tone quality, due to damping of high dissonant partials.

2. The more sharply pointed the contact surface, the smaller the actual mass of felt presented to the string and the fewer the upper partials around the contact point to be damped by the contact. Hence, a pointed hammer, other things being equal, evokes a less mellow and more complex tone.

3. The greater the velocity of travel to the string, the more rapid will be the rebound, since action and reaction are equal and opposite. Therefore the harder the hammer-stroke the less mellow will the tone quality be, other things being equal.

4. For the above reason, also, a lighter hammer will rebound more quickly than a heavy hammer on a light hammer-stroke and the heavy hammer will rebound more quickly on a stroke powerful enough to move its weight freely and derive the velocity-advantage thereof.

The Voicing Problem. The business of the voicer or tone-regulator is to exert such influence as can be exerted by treatment of the hammer-

felt, upon the tone-quality of the piano. Fundamentally, the tone-quality is settled long before the voicer sees the piano. The design of the scale, the general construction of the piano, the choice of striking points for the hammer; these and many other details have already determined the tone quality before any treatment of the felt is considered. The sole business of the voicer then is to smooth out, to improve if he can, what has already been set forth; and if he cannot improve, at least to put the best appearance upon things and to make sure that the piano goes out into the world under the most favorable tonal conditions. That is the voicer's business, and he effects his results by the processes of hammer-treating which I describe below.

Prior Condition of the Hammer-Felt. In the first place, let us keep in mind that the top-felt is less than an inch deep over the under-felt and molding at the point of contact in the bass, tapering down until it is hardly thicker than the felt of a hat, at the highest treble. This top-felt is fastened over the under-felt and molding in such a way as to stretch the upper while compressing the under surface. A structure like this must be more or less uneven in texture and certainly rough on its surface, and any attempt to better its condition in these respects through a process of working up the texture of the felt must take into consideration

that it is in both tension and compression, with a constant tendency towards pulling apart its fibres and disrupting its structure.

Smoothing the Surface. Before any judgment can be formed rightly regarding what may have to be done to a set of hammers in order to obtain the best possible tonal result, the surface of the top-felt must be made as smooth and as even as possible. This the voicer does by a process generally called "filing." A strip of ⅛″ hard wood is taken, about wide enough to cover the surface of a hammer when laid over it, with some space to spare, but not wide enough to interfere with the hammers on either side. The strip is made about seven inches long. Several of these strips are obtained and covered with sandpaper by the simple expedient of cutting a strip of the paper to the same width and twice the length and then gluing it over the one edge and down both sides. The loose ends are trimmed off where the hand grasps the instrument. Some of the strips are covered with No. 2, some with No. 1 and some with No. 0, sandpaper.

Filing. The "sandpaper file," as it is called, is used for the purpose of rubbing away the rough uneven particles and fibres of the felt so as to produce an uniform surface. The technique of the operation may easily be acquired, but practice and patience are requisites to success. The action is

laid on its back away from the piano, if this be an upright, or is taken out with the keys if it be that of a grand, and placed on a table or bench. The operator sits with the backs of the hammers nearest to him. Taking one of the hammers between his thumb and first finger he raises it above the line of the others and, grasping the file in the other hand so as to leave as much of the sandpaper available as he conveniently can, he draws the file along the striking surface of the felt, beginning at the bottom of the under side of the hammer and drawing the file in a series of light strokes towards the top or crown where contact is made with the string, *leaving the actual crown untouched.* In this manner he smooths out the surface, rubbing away the rough outside crust of the felt and drawing this latter up to a curl at the crown. By so doing the position of the crown is indicated and any flattening of it avoided. Then the hammer is attacked in the same way on its other side and the smoothing out is again terminated at the crown, so that now the hammer looks like a bald head with a little tuft of hair at the very top; a sort of Mohammedan top-knot. During this apparently quite simple process, however, it is well to remember that (1) the strokes must be made with the file absolutely square on the surface of the felt, or the contact surface will be spoiled. (2) The file must be drawn just with enough pressure to

take off the rough outer crust or skin, but not hard enough to make dents in the surface or to disturb the shape. Careful practice is therefore necessary, as well as a good deal of patience. Moreover, the high treble hammers which have so little felt on them must be very carefully treated, or their felt may be all filed away, leaving a bare spot, showing the wood underneath. This first smoothing is done with the No. 2 paper.

First Needling. The voicer now turns to the needles. Having given the surface of the hammer a preliminary smoothing out, he must attempt to produce an uniform texture in the interior. The object of so doing is to furnish a cushion for the immediate contact with the string, which shall be relatively resilient and uniformly yielding, against the harder under-felt and still harder wood molding. This upper cushion, however, must not be mushy at the crown or actual place of contact, nor must its surface be broken up and its fibres disrupted by unscientific jabbing with needles. On the contrary, the object is to work the inside of the felt so as to leave the outer surfaces as far as possible intact, while conforming to the requirements noted here.

The voicer therefore uses a needle holder containing three No. 6 needles, set in a row and projecting not more than one-half inch from the handle. This handle should be of such thickness

that when grasped as if it were a dagger with the point of the blade (the needles) downwards, it may be held without cramping the muscles. Thus grasped, it is used to stab the felt, in the manner following:

The hammer to be treated should be supported upon a block laid under its stem, so as to raise it above the line of hammers. Such a block is usually made wide enough to support three hammers at a time. The needle is firmly grasped in the right hand while the left hand steadies the hammer. Strokes are made by firmly pressing the needles down into the felt, on each side of the crown alternately, as far as they will go, not stabbing hard but pressing firmly, avoiding the crown and gradually working down on each side thereof to the very bottom of the top-felt. The needles should enter the felt like the spokes of a wheel, of which the under-felt represents the hub.

It is necessary for the voicer to estimate from time to time the condition of the felt and the progress of his work. At the beginning, before he has filed the hammers, he will of course have tested the general condition of the tone and will also have estimated the hardness of the felt. His work must continue until the interior of each hammer is in an uniformly resilient condition, without uneven lumps anywhere, but especially without any picking up of the surface or tearing of the fibres, and

without touching either the crown or the underfelt.

"Picking Up." The abominable practice of "picking up" the felt by digging with the needles as if one were digging potatoes out of the crown of the hammer, cannot be too strongly condemned. It does the very thing which should not be done: weakens the already tightly stretched sheet of felt by breaking the fibres and crushing the structure at its surface. The consequence is that the entire crown is soon broken up, its indispensable firmness is destroyed and its contact surface is made mushy and ineffective, while the interior of the hammer is left virtually in its original state. Thus the purpose of voicing is entirely missed. The needle-work should be done as indicated and in no other way; continuing until it appears by the "feel" of the felt that each hammer is well worked inside.

Trimming the Crown. The voicer now trims off the felt tuft or "top-knot" on the crown of each hammer with his sandpaper file, and replaces the action in the piano to test the tone. It will then be found, probably, that the quality is more or less mellow, but that there is much unevenness, some hammers being harder than others. The voicer therefore tests the tone quality by first running over the piano, a few hammers at a time, with a soft touch and then in the same way with a hard

touch. The tone quality ought to be alike in both cases. Also the tone throughout should be of even mellowness. To remedy unevenness the voicer uses his needles as before on the faulty hammers, again avoiding the crown, until the tone quality is evened up on a moderate touch. He then tries each hammer on a hard stroke and if the tone quality hardens too much when the stroke on the key is very strong, the voicer takes a needle holder containing two ¾-inch fine needles and with these takes a few "deep stitches," as they are called, down into the top-felt; avoiding the under-felt and the crown. This will remedy the trouble, which was due to the interior not having been worked sufficiently.[1]

Second Smoothing. The hammers are now smoothed again, with finer paper on the file, and any specially hard hammers that may have been noted are needle-worked until they are in good shape. The action is then replaced in the piano.

The "Dead" Tone. If the work has now been done rightly, the tone will be mellow and even on all kinds of touch, but with a sort of "deadness." One feels that it needs to be "livened up"; and this can be accomplished in the following manner:

Ironing. The action being again taken out, each hammer is carefully ironed with a hot iron. This

[1] Actually of course, every change in key velocity produces a change, slight but more or less perceptible, in the quality of tone. See on this point "Acoustic Design," Ortmann, Redfield, etc.

tool is best made from an old 1½-inch chisel, of which the blade has been cut off below the edge. Let this be heated until a drop of water touched to it evaporates and then let each hammer be well pressed with this on both sides. One side is held with the hand while the iron is being pressed into the other side. The operator continually directs the pressure upward towards the crown so as to press the body of the felt in the same direction. This is done on both sides of each hammer until the felt is well scorched and blackened.

The file is then applied again and the scorched felt cleaned off. The action is replaced in the piano and if the work has been well done the tone will now have been "livened up" and made clear.

The Crown Stitch. If there is any unevenness still to be noted in the tone quality, or especially if any hardness be observed anywhere, one or two gentle pressures into the felt, down through the crown with a single fine 1-inch needle, will remedy the trouble.

This, or something equivalent to it, is the process of voicing as carried out in the best factories.

Qualifications of the Voicer. A good ear for tone-quality is the principal qualification necessary for the voicer. The mechanical technique is soon acquired when the necessary feeling is there. To know what are the physical requirements of

piano tone is of course the business of the designer, just as the same man should also know how to insist on the various works of construction being carried out according to his prepared design; but even so the voicer himself should be equally scientific and equally able to take upon himself the function of a critic.

For instance, the voicer in the factory may perceive that the striking distance is somewhere wrong, and in that case it is his duty to insist on changes being made which will remedy the conditions. It is his duty to watch carefully all points of the design and construction which have relation to tone, and to suggest such improvements as his own knowledge leads him to discern. These are counsels of perfection, but they are necessary nevertheless.

A fine ear for tone-quality may be acquired by patient study of the physics of piano construction and by constant practice in the art of voicing. No other possible road can be recommended or even suggested. The aim and end of voicing is to make the piano sing beautifully, and only constant work on the piano makes this idea possible of realization in one's mind; an indispensable preliminary to its realization in concrete form.

The Ideal. The ideal piano tone is that in which a wave-form, including in the middle regions all partials up to the twelfth, shall be evoked more or

less fully according to the conditions of touch. It is the object of the piano hammer to make this tone possible; and of the voicer to carry out the technical processes necessary to prepare the hammer for its tonal work.

The matter of repairing old hammers, and cognate matters relating to the care of the hammer in used pianos, are discussed in the next chapter. The rules here laid down for the work of voicing are of course based on the practice of factories; and the tuner who studies this chapter is expected to understand that his practice must be modified in accordance with the condition in each case. Old pianos cannot always be treated exactly as described in this chapter, although every one of the rules and directions here given for each of the processes described and explained, is to be followed at all times. This is important: to follow the entire process may sometimes be out of the question, but every time a needle or a file or an iron is used, the directions given above should be remembered, and, so far as possible, followed out.

Care of Tools. One point remains. In using his tools the voicer should be careful about keeping his sandpaper files always covered with fresh paper, and about renewing his needles whenever they become dull at the points. Worn sandpaper and blunt needles prevent good work and cause waste both of time and of energy.

Chapter X

REPAIR OF THE PIANO

Definition. Piano repairing, for the purpose of the present chapter, is held to include all the work that the tuner may be called on to do on upright or grand pianos after they have taken their places in the purchasers' homes. In chapters which have gone before I have said a good deal about the technical processes of piano construction and adjustment, but these remarks have been concerned with the piano in course of manufacture. The special subject of repair and adjustment of used pianos deserves and requires a special chapter.

Square Pianos. The square piano is obsolete, but I have included at the end of this chapter some brief remarks on certain peculiarities of these old instruments.

Classification of the Subject. In order to make the subject more intelligible, I have adopted the following classification, marking out the subject in subdivisions and discussing the particular topic of adjustments and repairs specifically for each. (1) Tuning pins, wrest-plank and strings, (2) sound-board and bridges, (3) action, keys and

hammers, (4) pedal action and trap-work, (5) varnish.

Tuning-Pins and Wrest-Plank. Old pianos often suffer from what may be called a sort of general break-down of structure especially noticeable in the wrest-plank or tuning-pin block and in the frame work which supports the same. One symptom of such troubles is found in loose tuning-pins. Sometimes old pianos cannot be drawn up to pitch without breaking strings; or often again they will not stand in tune even when their strings are pulled up.

1. *Loose Pins.* Tuning-pins, of course, are held by the frictional resistance they develop against the cross-banded wood of the wrest-plank. If the wrest-plank holes have been worn through long use and much tuning, the pins will very likely be too loose for effective resistance to the string-pull. In this case, the obvious remedy is to hammer them a little farther into the block. If, however, this does not effect the required remedy, the tuner should insert a larger pin.

2. *"Jumping" Pins.* These may be remedied by the expedient of removing the defective pin or pins, and blowing a little powdered chalk into the wrest-plank hole. The cause is usually grease or oil which has soaked into the wrest-plank through some carelessness on the tuner's part; thus producing one of the most annoying of piano troubles.

Pins that "jump" cannot be manipulated in fine tuning, and much the same is true of pins that are too tight.

3. *Broken Pins.* The best way to handle a pin which has been broken off at the eye is with the tuning-pin extractor, which is a short steel head like that of a tuning hammer, but provided with a reversed thread tapped in it. The extractor is placed on a handle of its own or can be had to fit on to a tuning or T-hammer. It is worked by screwing it down reverse way on to the broken stump of the tuning pin. This cuts a thread on the stump and grips it tightly enough to enable the operator to pull it out of the wrest-plank, which is done by gently turning it in the plank hole until it is loosened enough. One must be careful not to get the head so firmly fastened into the stump of the pin that it cannot be unscrewed therefrom. It is best, in fact, to turn backward on the pins a little way after starting the thread and to keep on doing this from time to time while the thread is being cut.

4. *Wrest-Plank Holes Split.* The holes in the wrest-plank in old pianos sometimes are split across their mouths, so that it is necessary to plug them up and re-bore them. In doing this, maple dowels should be used for the plugs, which are driven in with glue. The hole is first reamed out somewhat and a dowel driven in to fit tightly, so

that when the hole is again bored for re-insertion of the pin there will be enough dowel left to act as a bushing all around.

5. *Upright Wrest-Plank Loose.* It is better not to touch an upright wrest-plank that is loose unless one is quite sure what one is doing. Old pianos with open wrest-planks sometimes give way at the gluing between the wrest-plank and the back posts; that is to say along a line parallel with the hammers from bass to treble, so that the entire wrest-plank pulls away from the back, carrying the strings and tuning-pins forward with it. If such a case be met with, the tuner may sometimes be able to repair the plank as follows: Loosen up all strings, screw wrest-plank back into position by hand screws, and leave same tightened in place. Remove all lag-screws. Bore out lag-screw holes right through the wrest-plank and out at the other side of the back. Procure threaded square-head bolts of suitable diameter to fill lag-screw holes and long enough to stick out at the other side, together with washers for their heads and tails and nuts to tighten up on them. There should be at least five such bolts, and if there are not so many lag-screw holes, one should bore out extra holes through the plate and wrest-plank. Now, let the hand-screws be loosened, while hot glue is poured along and into the crack between the back of the plank and the back posts of the piano. Screw up

hand-screws again. Insert bolts with washers on the heads, driving them well through till the threaded ends emerge at the back. Put on washers and nuts at the ends and turn nuts down as far as they will go. Tighten hand-screws further to take up slack when bolts are turned in. Leave hand-screws on about four hours. Then take screws off, tighten bolts further if nuts will turn, clean off glue, file off ends of bolts or cut them off with cold chisel, if they stick out too far, and file clean, draw up strings again, tune. This method will often succeed perfectly. Don't try to use liquid glue.[1]

6. *Strings Rusted.* Do not rub oil on strings if they are rusted. They may be cleaned by rubbing with one end of a hammer-stem dipped in whiting, using alcohol to moisten. Rust at the bearings near the upper bridge, or on the agraffes, or on the belly-bridge pins, or at the hitch-pins, may sometimes be remedied by the use of a little oil carefully brushed on. But the use of oil on wire is not generally permissible.[2]

7. *Tuning-Pins Rusted.* The coils of strings around tuning-pins can be cleaned, as well as the pins themselves, by the use of a string and pin

[1] A grand wrest-plank that has split should be unscrewed from the iron plate, taken out, and sent back to the factory to be replaced. The tuning pins must be removed before the plate screws are loosened.

[2] Rust-resisting piano wire is now becoming available.

polisher, a device whereby a rag carrying metal polish is pushed in and around the coils where the hands alone cannot go.

8. *Strings False.* False beats have already been referred to (*supra,* Chapter II), but the tuner will often find that his ingenuity is strained to overcome the clashing between several strings, when each of them generates false beats. It is sometimes possible to tune one string against the other, as it were, so as to play off one set of false beats against another. In bad cases, one must remove the old wire and replace it.

9. *Bass Strings "Dead."* Bass strings sometimes go "dead," losing all their beauty of tone and emitting a dull hollow sound. One may try loosening the string, putting a hook in the hitch-pin eye, twisting the string a few times and then replacing it as twisted. This will often take up a loosening in the covering wire that is a frequent cause of dead tone. In bad cases, one must remove, and replace.

10. *Bass Strings Rattle.* This is usually through loosening of the covering wire or of the pins on sound-board bridge. Remedy accordingly.

11. *Treble Strings Rattle.* Causes are as above. Sometimes the upright pressure-bar is loose, but be wary of tightening it too much. Grand agraffes which are made of brass may become worn at the string holes and must then be replaced.

12. *Obtaining New Bass Strings.* Bass strings must be made to order. In getting new ones, one sends along the old strings, whether one, a few, or a whole set.

13. *Defects of Iron Plate.* Apart from screwing down the bolts on an unstrung piano the tuner can do virtually nothing with defective plates save send them to the factory. Broken plates can be re-welded by the oxy-acetylene process.

Sound-Board and Bridges. 14. *Sound-Board Split.* Small splits are not dangerous and do not affect tone unless they cause the board to loosen at the edges. Splits are caused by alternate compression and expansion of the wood due to weather and cognate conditions. If it is necessary to repair a split, one may open it up with a sharp knife until it is even in width from end to end, and then insert a "shim" or short strip of sound-board lumber, which may be obtained in quantities from any factory, using hot glue and hammering the piece well in. Shims are triangular in cross section and are driven in sharp edge down. When dry, they must be trimmed off, and smoothed down.

15. *Ribs Loose.* Sound-board ribs are glued in place. If they spring out of place they may be screwed down by drilling small holes into them from the front of the sound-board and then driving screws from the same side into the rib, through

the board, with a bridge button at the head of the screw to take up any uneven thrust. Glue brushed over the surface of the board where the rib has sprung also helps.

16. *Sound-Board Rattles.* Usually in grand pianos the trouble is that something has dropped on to the board. One may get a long strip of thin steel like a corset steel, fasten a little pad of cloth on one end and explore surface of sound-board therewith, thus removing dust and grit, pins, pennies, etc. In the upright piano, the fault is usually loose bridges, or splits. Of course the same conditions occur in the grand piano too.

17. *Bridges Rattle.* Strings rattle on bridges when pins are loose. It is well to drive the pins in farther and file over their heads if necessary. In bad cases one may put in longer pins. If the bridge is split, one may saw out the split section to a point slightly below the lower ends of the pins and send this to the factory. A new part will be returned bored and pinned, ready to be put back in place, which should be done with glue and screws. Bridges also rattle when the buttons behind are loose or when they have sprung from the surface of the sound-board. Remedies are obvious.

18. *Bass Bridge Loose.* Bass bridges sometimes come away from the sound-board, especially when they are of the extension variety. If an extension

bass bridge splits in half, one must remove the bass strings and re-fasten the split part with glue and screws.

Action, Keys and Hammers. 19. *Defects of Upright Action:*

Flanges rattle.	Tighten.
Flanges being loose, hammers "click" when striking strings.	Tighten.
Hammers "click" when striking strings.	Hammer heads loose on stems, back-stop stems loose in back-stops, hammer stems loose in hammer butts. Remedy—re-glue.
Hammers loose on centers.	If center is split, put in new hammer butt. If pin is loose in flange, use larger pin or new flange. Tighten on flange.
Hammers don't strike squarely.	Stems are twisted. Heat stems with alcohol lamp and bend hammer heads into correct position.
Center bushings worn.	Cut strip of bushing cloth triangular in shape, coming to point at apex. Twist it to shape of a cone, and spread on it some glue. Push point in through flange holes whence old bushings have been removed. Pull through as far as required. Then cut off bushing cloth, trim, and let dry. This can be done on several flanges at once.
Center pins too tight.	Push pin in and out a few times, or try smaller pin. Don't ream bushing if you can help it. Don't oil bushings.
Bridle-tapes missing.	Usually this means mice. Cut away old stumps of tape and insert new tapes with tape inserter. If no inserter is available, cut groove in bottom of butt, near where tape goes in, with fine hack saw, fold tape over, and glue in groove. See that length is right.
Bridles squeak on wires.	Remove from bridle wires, clean off all rust. Replace.
Keys stick when depressed.	Ease front rail mortise with key-pliers.

Keys stick on balance rail.	Ease balance rail mortise.
Keys rattle and shake.	Re-bush mortises, using bushing cloth and wooden plug to hold cloth while it is drying. New key top buttons can be had in sets for old keys.
Keys sunk in middle.	Replace worn punchings on balance rail and re-level. If necessary, build up key-frame with cardboard under balance rail.
Keys rub in front.	Re-space and straighten.
Keys sink. Key level uneven. Lost motion. Back-checks block. Hammers block. Repetition bad.	See Chapter VIII (regulating).
Dampers buzz on strings.	Straighten on strings.
Dampers don't rise.	Bend damper spoons.
Bass dampers catch.	Straighten dampers and re-bend wires.
Jack action feeble.	Strengthen springs under jacks.

20. *Defects of Grand Action.* Nearly all the above remarks on the upright action apply also to the grand, but the following additional instructions are also useful:

Hammers out of line.	Re-space.
Hammers don't check.	Re-bend back-checks.
Hammers re-bound too high.	Regulate repetition lever to trip a little lower.
Hammers strike loosely.	Probably the contact-roller under the hammer butt is flattened. Releather.
Hammers squeak.	Perhaps the contact-roller is worn bare. Springs in action worn through felt bushings. Rust on springs. Remedy accordingly.
Dampers stick.	Bushings in rail are swelled.
Dampers don't damp.	Straighten them on the strings, clean felt, regulate their fall.
Keyboard rattles.	Key blocks not tight down. Or key-frame warped. In latter case, glue cardboard between frame and key-bed.

21. *Trap-Work in Upright Pianos.* Old style wooden trap-work often shakes, rattles and suffers from lost motion. Use black-lead for squeaks between springs and wood, and soap for trap-pins. One may oil the pedal bearings when these are of metal and take up lost motion at the adjusting points. It is well to note whether the soft pedal rod shakes at the top or rattles. This is a common defect. Use felt punchings for taking up lost motion where no screw adjustment exists. Vaseline on coiled springs stops squeaks.

22. *Trap-Work on Grand Pianos.* The only difference lies in the fact that the grand trap-work is placed in a separate lyre. Sometimes the pedal foot sticks in the lyre, or there is lost motion due to worn bushings. The trap levers are usually found under the key-bed and in modern instruments a screw adjustment on the lifting rods permits the taking up of lost motion. Other difficulties can be remedied as in the upright.

23. *Varnish.*[1]

Bruises.	Fill in with melted sealing wax, if deep, then cover with film of melted shellac, which sandpaper down, and touch up with French varnish. To polish this, rub with powdered pumice stone and pad, using water to moisten, finish with rotten stone and pad, and then with hand moistened with rotten stone and water. Oil off as below (Oiling off case).

[1] Lacquer finished cases should be treated according to directions obtained from piano manufacturer.

Blue look on case.	Due to moisture and dust combined. Avoid polishes. Simply wash off case with soap and water and dry with chamois leather.
Light scratches.	Run down with powdered pumice stone and finish as above. Touch up with French varnish if necessary.
Deep scratches.	Fill with shellac, and proceed as above.
Renovating old case.	Scrape off old varnish, then smooth case with sandpaper, then with pumice stone rough. When surface is clean, revarnish with two coats rubbing varnish, two days apart, rub down rough with pumice stone and water, flow over with flowing varnish and then polish as below.
Polishing varnished case.	After flowing coat has dried (5 days) rub down with pumice stone powder, water and felt pad till all parts are flat. Then rub out scratches with rotten stone, water, and pad. Finish with hand till brightened up. Oil off as below.
Oiling off case.	When all traces of powder, etc., have been removed, rub lightly with cheese cloth on which has been poured some lemon oil. When this has been done well, wring out another cheese-cloth in alcohol and wipe off lemon oil. Alcohol must be almost dried off before using the cloth.
Checking of varnish.	This occurs in all pianos after exposure to domestic conditions. Repolishing with pumice stone, and thence as directed above, will often remedy. But varnish always checks.

24. *Ivory Polishing and Repairing.* Ivory keys get yellow. They may be scraped down white again with ivory scraper or by fastening down entire keyboard in front after removing sharps and then rubbing back and forth with wooden block covered with No. 1½ sandpaper.

To polish, rub ivory with whiting and alcohol.

Touch up sharps with French varnish.

To replace badly worn or loose ivories, take new strip of ivory, and after making some deep scratches in wooden top of key to assist glue in holding, spread over wood some glue whitened by mixing a little whiting in the glue pot. Put ivory on and fasten with special ivory glue clamp or by wrapping tightly with string. The clamp is better. Never try to use liquid glue. There is an ivory cement on the market.

25. *General Remarks on the Square Piano.* Although very few square pianos remain in use, the tuner sometimes has to do work upon these old instruments. Their principal defects may be summarized as follows:

Defects of sound-board and bridges.	Sound-board sags in middle sometimes enough to cause hammer-rail to touch it.
	Pins in bridges loosen.
	Bridges split.
	Sound-board splits.
Defects of case.	Wrest-plank sometimes sinks so that it is necessary to pare off some of the under surface to enable hammer-rail to have free space.
	Key-bed often sinks in middle and lets down touch of keyboard. Remedy is to build up under key-frame.
Defects of action.	
Hammers loose.	Tighten split flange, or if flange is fixed put in larger pin. But see that hammer moves freely.
Hammers don't strike squarely.	Re-space hammer butts.
Hammers twisted.	Bend stems over with alcohol lamp.
Hammers rattle.	Glue loose somewhere. Investigate and re-glue.

Hammers Worn.	Get new hammers by removing old ones and sending them in as samples. Re-capping with leather is usually very poor policy.
Jacks sluggish.	Springs are weak. Replace or strengthen.
Excessive lost motion in action.	Screw up jack rockers but leave enough play to assure jack getting back into place under hammer.
Keys rattle.	See directions for upright.
Dampers rattle.	Bushings of lifter wires are loose or worn.
Dampers stick.	Bushings swelled. Heat lifter wire and push in and out of bushing until same is expanded.
Dampers don't damp.	Probably damper-levers don't co-act with lifter wires. Re-space.

Other defects can be understood and remedied by study of previous instructions on upright and grand pianos.

26. *Tools.* The importance of good tools can hardly be overstated. There is no greater mistake than to suppose that one can do good work with bad tools. Many special tools are manufactured for the use of piano makers and tuners, and all of them are useful. Action regulating calls for many tools of special design, such as regulating screw drivers, spoon benders, key spacers, key pliers, wire benders, and others of the same sort. Special conveniences are also to be found such as pocket glue pots, center pin carriers, wire carriers, and similar articles. The tuner should take pride in having the best possible tools and in carrying them most conveniently and accessibly. Some of the tool kits put up by various manufacturers, containing complete sets of tools for all kinds of out-

side work on pianos and player-pianos, are extremely attractive and practical.

One may summarize the whole case for good tools in these words of advice: Get the best tools, learn to use them skilfully and keep them in perfect condition. This alone may not make a man successful, but unless he has this respect for, and care of, his tools, he certainly will be unsuccessful.

Nor can one afford to neglect the matter of appearance. The tuner does much of his work in the customer's house. He is largely judged by the appearance of his clothes, by his manner, and likewise by the professional or unprofessional appearance of his tools. A neat case of bright, clean, fine-looking tools is an advertisement: it is also an aid to efficiency.

Chapter XI

ELEMENTARY PNEUMATICS

It is not my intention in the following chapters of this book to write an exhaustive treatise on pneumatics. Elsewhere I have subjected the piano-player mechanism to treatment of a technical sort at some length. The reader who wishes to be thoroughly acquainted with the player mechanism, and is not satisfied merely to know that which every tuner must anyhow know today about players, should study the subject systematically.[1]

Scope of These Chapters. In this and the two following chapters, then, I undertake to set forth briefly (1) the fundamental principles of pneumatic player mechanism, (2) a general description of the modern player-piano in its pneumatic aspect and (3) such instructions as experience shows to be most useful in the adjustment and repair of defects. The treatment is such that the reader will have no difficulty in following everything set down here.

The Mechanism. The player mechanism is self-contained and entirely independent of the piano. It is usually built to fit into waste space within

[1] The book referred to is "Piano-Playing Mechanisms," published by Edward Lyman Bill, Inc., N. Y., 1925.

the case of the upright, or underneath the soundboard of the grand. In its common embodiment it remains an addition to the ordinary upright, built within the case, but independent of and not interfering with the regular action, scale or soundboard. It can be withdrawn from the piano case very readily and is in all respects separate from the musical instrument itself.

The function of the player mechanism is to render musical compositions by playing upon the piano action, under the control exercised by a perfected traveling sheet or "music-roll." The player mechanism runs on power furnished by bellows which are either foot-blown or power-blown. Various means for expression are provided, controlled either automatically or at the will of the performer, the objects of which are to permit, as required, variation of speed, use of damper lift, loud and soft stroke of hammers, and division of melody from accompaniment parts. All these requisites are made possible by the use of simple auxiliary devices.

Source of Power. The blowing power is furnished either by the performer's feet or by an electric motor. The ordinary upright player piano invariably is foot blown. The "reproducing" (automatic expression) player piano is nearly always power-driven. The operation of the bellows system is not at all hard to understand. In fact,

the entire player mechanism works on a system so generally simple that, once its principle has been grasped, the reader can reason out immediately the method of its operation and the function of any part.

Pressure and Weight of Air. The air of the atmosphere in which we move and which we breathe is invisible and virtually intangible. Yet it is to be reckoned with just as if it were so much iron or wood. Its density is less than that of the other materials mentioned, but is measurable nevertheless. Like all forms of what is called matter, the atmosphere is ponderable. A column of air one inch square and the height of the atmosphere weighs very nearly 14.75 pounds (236 ounces); so that we may say that the air of the atmosphere exerts a pressure at its bottom (the surface of the earth), of about 14.75 pounds per square inch.

Expansion. Air is a gas and all matter in a gaseous state has the property of expanding continuously to fill any space in which it may find itself. This expansive property, together with the weight of air, is the foundation of the operation of all pneumatic machines.

The air normally fills at normal pressure all closed spaces capable of containing air. It is everywhere and always present at normal pressure, unnoticed and unconsidered, until by some artificial means it is either rarefied or condensed.

Then work can be done by means of it. If a closed bag, which is normally filled with air according to the natural facts of the case, be shut off and closed so that no more air can get into it from the outside, and if then the bag be enlarged, without any more air being allowed to flow into it, the contained air will have to expand to fill up the enlarged space. In so expanding, the air is acted on like the rubber in a rubber band which is stretched. It becomes thinned out, so that any cubic inch of it now weighs less than a cubic inch of it weighed before it expanded. Hence the pressure exerted by any quantity of it is less after expansion than before. Hence, again, the atmosphere outside, which has retained its normal pressure of 14.75 pounds to the square inch, is able to exert an effective pressure on the outside walls of the bag, because the inside pressure is reduced owing to the expansion of the bag; and hence the balance between the outside and inside air is disturbed.

Disturbance of Balance. The player mechanism operates entirely through this disturbance of balance as between the free air of the atmosphere and bodies of air contained within enclosed spaces.

Look at the illustrations, Figures 21 and 22, which show the various parts of a player mechanism drawn out in the simplest possible way to show the operation of each part, but not drawn in proportion or according to any particular exist-

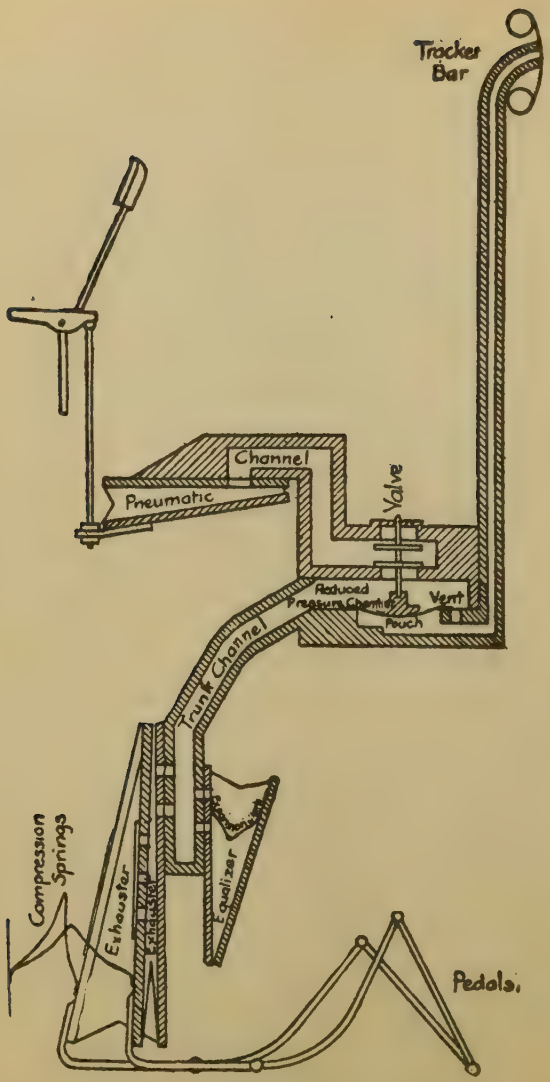


FIGURE 21

Essential parts of player mechanism, pneumatic open; (not to scale).

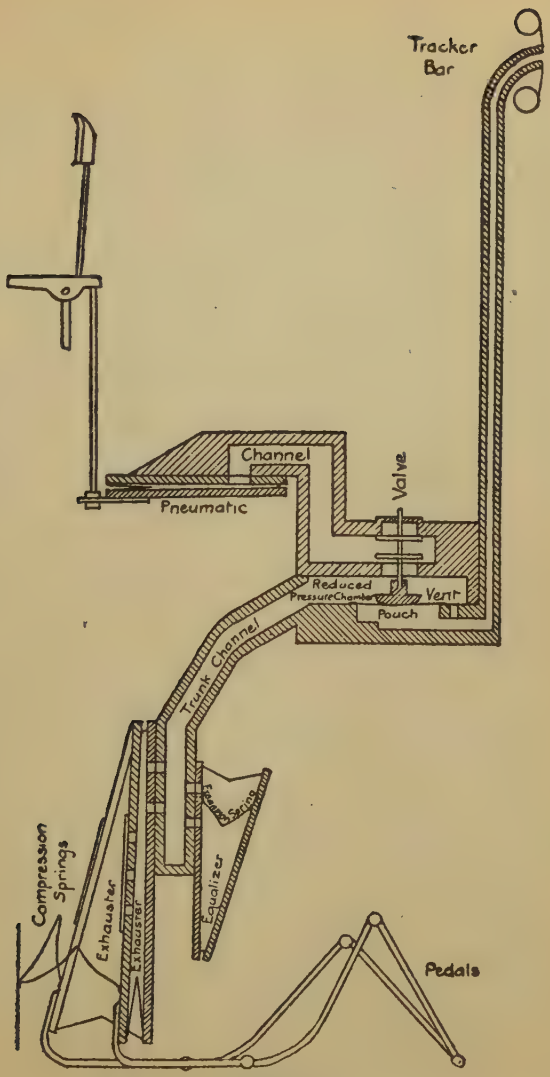


FIGURE 22

Essential parts of player mechanism, pneumatic closed; (not to scale).

ing player. In fact the object of the drawings is to show only the operation of the principle.

Simplest case of Pneumatic Mechanism. At the bottom of each illustration will be observed the bellows with two "exhausters" operated by the foot pedals, and one "equalizer." One of these exhausters is open and the other closed. But let us suppose that the player is in a state of rest with, therefore, both foot pedals untouched and both exhausters closed. The compression springs behind the exhausters hold them closed normally. Well, now, the exhausters being normally closed, the reader will observe that (1) the outside air can find its way into the "pneumatic" through the channels and the top of the valve; (2) the long channel from the tracker bar, over which the perforated paper moves to the valve pouch, will also contain any air that may have flowed into it when a perforation in the paper was registered with the tracker-bar hole; and (3) through the little "vent," which is just a pin hole in a cap, the atmosphere flowing in from the tracker bar will also fill the reduced-pressure chamber and therefore the entire bellows system, which is in connection with it. This is the normal or at rest condition.

Operation of Exhausters. If now, the foot is placed on a pedal and one exhauster is pushed open, see what happens. Assuming that the

tracker-bar channel is sealed by the paper for the moment, as when no note is being played, it will be seen that this opening of the exhauster simply enlarges the whole inside cubical content of the player, which in fact, is made larger inside by just the volume of the exhauster. True to its nature, therefore, the air in the various parts of the player expands equally to fill up this space. But the illustrations show that a flap or strip of leather covers the openings between the inner wall of the exhauster and the interior of the player. This strip, however, is pushed aside by the rush of normal-pressure air into the empty, opened exhauster, which continues until the pressure on either side of the strip is equalized. Therefore, a quantity of air filling the exhauster, but at lower than normal pressure, is now trapped in the exhauster, since it cannot get back through the door which it opened once and is now holding closed (the strip); for this door is held shut by a spring just strong enough to keep it against the pressure on the inside of the player, and further, is of course held by the pressure now in the exhauster. But, the exhauster being now all the way open, and the pedal all the way down, the heavy compression-spring outside tends to close the exhauster again. Besides, the foot-pressure is now naturally released for the return of the pedal. Therefore the exhauster begins to close and in closing squeezes

the air inside it, which is trapped there and cannot get back inside the player, until it is compressed enough to force its way out through the outer strip or flap into the atmosphere, when it is impelled by the closing of the exhauster. Once the air is squeezed out, the exhauster is shut, and anyhow, no more air can get back inside through the strip or flap which presses on the outside of the exhauster. Therefore, we see that one opening and closing of the exhauster withdraws a definite quantity of air from the interior of the player and expels it into the atmosphere. Therefore a "partial vacuum," as it is called, is set up inside the player; or, in other words, the pressure of all the air inside the player is lowered.

Valve. This being the case, the atmospheric pressure on top of the valve holds it down firmly on its seat and shuts off the reduced pressure chamber from the outer air, while conversely the pneumatic is open to that air and therefore remains at rest.

Reduced-Pressure Chamber. Thus the situation when the pedals are being operated is as follows: Pressure of air is being constantly reduced inside the player, in the reduced-pressure chamber, in the tracker-bar channel (though on account of the smallness of the vent, to a smaller degree), in the trunk channel between bellows and pneumatic action and in the equalizer. Now suppose

that a hole in the paper registers with the tracker-bar hole:

Operation of Valve. Immediately, the atmosphere, which has of course, been pressing against the paper, finds its way down against the reduced-pressure air, through the tracker channel and under the pouch, losing a little by the way through the vent. The pouch being larger than the top of the valve button, rises against the pressure on the button, and lifts the valve spindle with its buttons. At once, as may be seen, outside air connection with the pneumatic is shut off, while connection is simultaneously made between the pneumatic and the reduced-pressure chamber. Hence the heavy normal air in the pneumatic expands into the reduced-pressure chamber, reducing the pressure in the pneumatic. The atmosphere therefore presses against the moving wall of the pneumatic, closing the same and putting the piano action into operation.

When the perforation passes over and the paper again seals the tracker-bar hole and channel, the normal air under the pouch and in the channel no longer is re-inforced by supplies from the outside. In consequence (since the bellows are operated continuously and the reduced pressure chamber always therefore is in a state of partial vacuum, being never in contact with the open air except at times through the very small vent), this normal

air in the channel expands into the reduced pressure chamber as quickly as it can move through the vent, air being elastic in all directions. Therefore, partial vacuum again exists in the channel and under the pouch, so that the valve-stem is no longer held up with its buttons, but again sinks down and is held down by the atmospheric pressure on its top button. Therefore, again the pneumatic is shut off from the reduced pressure chamber and placed in contact with the atmosphere, so that it fills with air at normal pressure, and forthwith opens. This operation may be repeated over and over again, quite as rapidly as the piano action can operate, and, in fact, even more rapidly; provided the necessary sequence of perforations is present on the paper roll.

This is the operation of the player mechanism. But we have yet to speak of one important accessory: the equalizer.

Equalizer. The equalizer is a reversed exhauster. Normally it is held open by a spring. It is also, as will be seen, connected pneumatically with the remainder of the bellows system and with the upper action of the player. When the exhausters begin their work, the air in the equalizer expands along with the rest, and part of it moves outward to the air, so that the pressure in the equalizer is also reduced. If the pressure is reduced enough to overcome the expansive power of the spring

(which never exceeds 8 ounces per square inch of area on the moving wall of the equalizer and usually is much less, so that a displacement of about 3 per cent of the contained air is enough to enable the atmosphere to balance the spring and neutralize it), then the equalizer starts to close. While closing, it does no effective work, but is in fact a drag on the bellows. When, however, owing to an increase in the number of tracker-bar holes open, or to slowing up of the pedaling, or increased speed of the motor, or to any other cause, the effectiveness of the exhausters is reduced for a time, the equalizer, forced by its spring, begins to open, and in opening becomes, of course, another exhauster, automatically displacing air from the player and holding it till the exhauster can take care of it and expel it. This is the function of the equalizer.

Of course, the reader is well aware that there are many variations of the simple system here described, but all depend on exactly the same principles, whether one or another kind of bellows be used, whether single or double valve system be adopted, and whether the most elaborate or the simplest expression devices be provided. In the next chapter, I discuss the commoner varieties of construction amongst the players usually met with.

Motor. The motor system is equally easy to

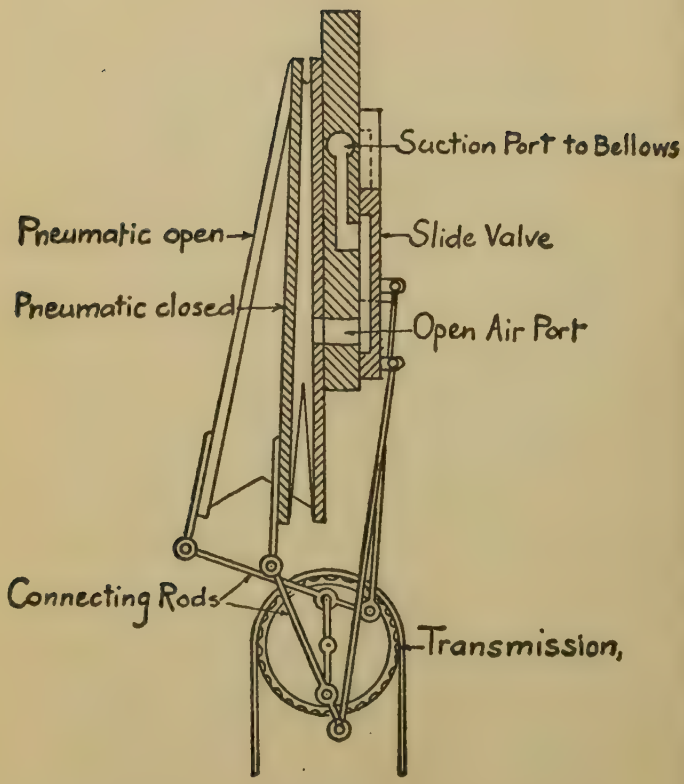


FIGURE 23

Sectional view of pneumatic motor, showing pneumatics, ports, slide valve, and connections.

understand. As will be seen by the illustration on the previous page, the motor consists of small bellows called "pneumatics," mounted on a block which is perforated with one long tube running through it from the bellows, provided with ports called "suction ports" which penetrate to the outside of the remote surface of the frame. Each pneumatic is also provided with a port which runs between its interior and the outer surface of the same block. A slide valve slides over the pair of ports belonging to each pneumatic and is connected with a crank shaft by means of a connecting rod, the pneumatic itself being also connected to the crank shaft.

Operation of Motor. Now, when the bellows are operating below and the suction port is in pneumatic connection therewith by means of the tempo lever which opens a gate situated in a suitable gate-box, the air pressure in the suction tube is reduced. When, therefore, a slide valve is in such a position that it covers both the suction port and the outer air port belonging to any pneumatic (see the illustration), the air in the pneumatic flows outwards into the suction port and thence into the channel and so to the bellows.

This causes the outside air to press against the moving wall of the pneumatic and to begin to close it. This closing moves the connecting rod and turns the crank shaft, which in turn brings the

slide valve along till the suction port is closed and the outer air port exposed to the atmosphere, when the pneumatic again fills and opens, thus continuing the rotary motion of the shaft and completing it. When a number of pneumatics, usually four or five, are arranged around a crank shaft at suitable angles, a continuous rotary motion is given to the shaft and the motor develops enough power to turn the take-up-spool around which the paper roll winds.

Motor Governor. The operation of the motor governor is equally easy to understand. As will be seen by the illustration on next page, air which travels from the motor passes into a sort of small equalizer, held open by a spring. In passing this, it goes through an opening which may be covered by a valve block, the movement of which depends upon the position of the moving wall of the auxiliary equalizer. The movement of this wall depends upon the power of its expansion spring. If this spring, for instance, is at such tension that it pulls back on the wall with a pull equal (say), to 3 ounces per square inch of the wall's surface, then the equalizer will close down as soon as the pressure inside is reduced enough to give the outside atmosphere more than 3 ounces effective pressure per square inch. In so closing it tends to shut off the travel of air through itself from motor to bellows and thus governs the motor so that no

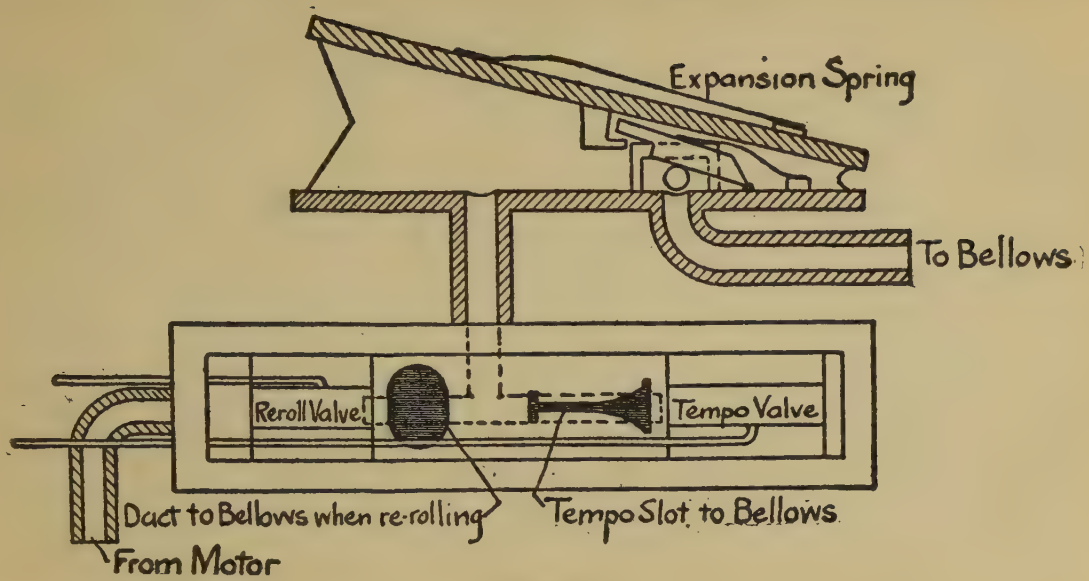


FIGURE 24

Motor Governor and Tempo-box in section (separation of re-roll valve from governor not shown).

matter how hard or how gently one pumps, that is to say no matter how much or how little partial vacuum there is, the governor acts accordingly, closing or opening as required, but always maintaining such an opening that increased velocity of air travel shall be balanced by smaller area of opening, or decreased speed by larger area, maintaining always the same pull on the motor and keeping its speed steady irrespective of the state of the pumping on the pedals.

Tempo-Box. In order to permit changes in speed or a full stop, the governor includes a tempo-box containing (see illustration), two valves operated by slides over them. When the re-roll slide is closed, and the tempo closed also, no air can pass from the motor further than to these slides, and so the motor stops. When the tempo slide is opened, air can pass through, and according to the area of the opening, as determined by the position of the tempo lever and hence of the tempo valve slide, the motor runs slower or faster. The more air is displaced in a given time, the faster it runs; and this is governed by the size of the opening. Steadiness is governed by the motor governor and speed by the tempo valve.

The re-roll valve is used to run the motor very fast when re-rolling the paper at the conclusion of the piece. In most players it is independent of the governing pneumatic, though the illustration

here, for the sake of simplicity, does not show such an arrangement.

Many other accessory devices are used in various players, but these I reserve for treatment in the next chapter, where I shall speak of the principal existing types of player and of the peculiarities of each. In the same chapter also I shall touch on valve-systems, accessories, individual peculiarities and so on, in just enough detail to enable the reader to recognize these when he meets them; and to understand their operation and duties.

Physical Facts. In conclusion, I append the following summary of physical facts, which should be learned by heart and carried in the memory:

1. Air, like all matter in any state, possesses weight; that is air is affected by the universal law of gravitation.

2. Air, therefore, exerts pressure at the surface of the earth.

3. This pressure is about 14.75 pounds per square inch at sea level, but being equal and uniform in all directions is normally not felt.

4. The normal pressure of the air cannot be used unless a body of air in which the pressure has been artificially reduced is placed in opposition to it. Then it can be used.

5. This principle of "disturbance of balance" is the foundation of the entire player system.

6. The player uses very low effective pressure.

Whereas a perfect vacuum would mean that the outside air could exert its entire pressure of 14.75 pounds to the square inch on the moving parts, we cannot obtain working pressures on the moving parts higher than from 1½ to 2 pounds per square inch. In other words, the degree of vacuum obtained inside the player does not exceed at the most 15 per cent and is usually less than 10 per cent.

7. All air expands immediately when its container is enlarged or when part of it is withdrawn from its container without more coming in. This expansion reduces pressure, in proportion to its extent.

8. The player bellows operate by enlarging the containing space, causing the contained air to expand, then by means of suitable flap-valves expelling the displaced air on the closure of the bellows, and thus producing a state of reduced pressure inside the player; so that the outer air can operate against the moving parts thereof by pressure on their outer surfaces.

The above statement of principles applies perfectly to every possible arrangement of devices, parts or accessories found in any player mechanism made.

Chapter XII

GENERAL CONSTRUCTION OF PLAYER MECHANISMS

Piano-playing mechanisms have been developed after two general types. One of these is the detached or cabinet player, consisting of a separate mechanism enclosed in a case and mounted on castors so that it may be moved about readily. It is secured in front of the piano, with its fingers resting over the piano keys; and when the piano is to be used for manual playing, it may be moved away. This type, self-contained and involving no modification of the piano, was the first to come on the market, and the earliest specimens date from the year 1897. Some five years after their first appearance, their popularity was menaced by the "player-piano," as it came to be called, which contains both elements in the one case. From that time, the prestige of the cabinet player declined, until today one seldom meets it.

The other type is of course the "player-piano" of today, consisting of a player mechanism built into the waste space inside the outer casing of a piano and combining in the one structure both the ordinary piano and the playing mechanism, in such a way that neither interferes with the other and

the piano can be played in the ordinary way if desired. I propose to give some general account of both types, although the "cabinet" player needs only brief mention.

The Modern Player Piano. The modern player piano consists of an ordinary piano, of which the case is usually somewhat widened, containing in the space between the action and the top and bottom panels, a playing mechanism for operating each of the eighty-eight sections of the piano action. This mechanism is commonly divided into two grand divisions known respectively as the Bottom Action and Top Action.[1] These I shall describe in turn.

Bottom Action. The bottom action is that part of the mechanism placed beneath the key-bed of the piano, and is commonly one self-contained piece of machinery. Sometimes a few of its accessory devices are placed away from it and connected with it by tubes. The bottom action itself comprises principally the exhaust bellows, the pedal action attached to them, and the equalizer system. This is known as the "bellows-system," and to it are commonly attached various subsidiary devices, such as the motor governor, the expression governor, the action-cut-off valve, and the pneumatic sustaining-pedal action. The bottom

[1] A recent player action by Pratt-Read Company comprises a compact housing of the entire action, bellows, stack and accessories, above the keyboard.

action is of course connected with the top action (comprising the pneumatic stack and spool box with motor), by means of two main air tubes, one at the left side connecting with the pneumatic stack and one at the right with the motor.

Bellows. The modern bellows system is a highly sensitive organism, comprising two exhaust units connected to foot-treadles, and one or two equalizers. The double equalizer system is the more common of late. The two exhausters are kept closed each by means of a spring of about 7 pounds pressure, while the equalizers (if there are two), are spring-expanded (kept open) by springs respectively of 14 and 28 pounds. The latter, or high pressure, springs are often re-inforced further by means of an extra wood-spring external to the equalizer and designed to come into action only when the equalizer is half closed. The idea of having two equalizers is simply to ensure that the bellows system shall not "go dead" on very hard pumping; which means that the two equalizers shall not both close up and remain closed until the tension has been relieved by momentary stoppage of pumping. With a good mechanism, well-made, and with heavy pumping, this might happen if the spring pressure on an ordinary equalizer were no more than 14 pounds total, for this would not be much more than 2 ounces per square inch on the wall of the equalizer. If the equalizer did remain

closed it would simply be out of action, for it is plain[1] that it does no work till it begins to open after being closed. Hence the double spring-pressure on the high tension equalizer.

Some are provided with a special device in the equalizer known as the "crash bellows" (though just why this name, I do not know). This is simply a small bellows placed inside the equalizer over the connecting passage which runs outward to the main channel and to the exhauster, in such a way that a sudden raising of the tension level, due to hard pumping, will close down the small bellows over the opening and for the moment cut off the equalizer, thus giving the bellows that much less air-space to exhaust and therefore increasing its relative power. As soon as the effect of the sudden extra pumping work has evaporated, the crash bellows again open and the equalizer is once more thrown into operation.

Motor Governor. The bellows system includes always, whether immediately placed on itself or at one side of and pneumatically connected with it, what is called a "motor governor." This device has been essentially described in the previous chapter and it is therefore now only necessary to remark that it is commonly fitted with a spring, adjustable for tension, and with some sort of adjusting screw for limiting the closing of its bel-

[1] Cf. Chapter XI.

lows. The speed of the motor is increased by increasing the tension of the spring. That is to say, the motor, irrespective of the tempo-valve, may be caused to move at a speed greater on any tempo valve position than originally it is adjusted to give on that position; and incidentally on all other positions. This general raising of the speed level on all positions proportionately may be accomplished by stiffening the spring. This simply means that the stiffer spring imposes greater resistance to the closing of the motor governor bellows,[1] so that, for any given rate of pumping, the cut-off valve in the governor closes less; but this again means, of course, that proportionately more effort is required to pass the displaced air through the larger opening. Thus the effect of stiffening the spring is indeed to increase the speed, but only by giving the opportunity to the performer to get that higher speed by harder work on the treadles, although the fact that the work is harder is usually not perceived.

In just the same way the tension may be released somewhat, with consequent quicker closing of the governor, quicker cut-off and lower general speed level.

Adjusting Screw. An adjusting screw is found on all motor governors, or on nearly all. Its object is to control the proportionate closing of the

[1] Cf. Chapter XI.

governor bellows. In some types this screw simply abuts on a block inside the governor so that, the farther the screw is turned in the more the cut-off valve is closed up. To determine the particular system used in any given case, one must know the player, or else must experiment with it to discover which method is used.

The point is that if the motor is unsteady on changes of pumping, the screw adjustment may be used to make correction of the fault. Such unsteadiness shows that the governor closes too much or too little, as the case may be. If the motor drags on light pumping, so that its speed falls, that shows that the governor closes too much, and that either its spring is too light or the adjusting screw must be turned to limit its closing. If the motor races on hard pumping, that shows that the governor closes not enough, or else that the spring is too stiff. If the general speed is right, then the fault is in the adjustment of the governor; which is corrected as described.

Expression Governors. Some players are fitted with an additional governor on the bellows-system known as the Expression Governor. The principle of its operation is of course identical with that of the motor governor, but the object of its existence is different. The motor governor exists to maintain a steady level of power, but the object of the expression governor is to enable quick changes to

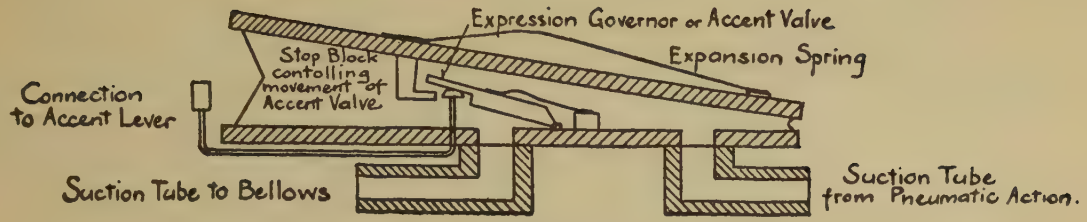


FIGURE 25

Sectional View of Expression Governor (Auto-Pneumatic type).

be made from a fixed governed low level to the ungoverned (high) level at which the exhausters of the bellows system are working at any moment. All sorts of detail differences are possible, and existing, with regard to the construction of such devices; but the type illustrated here (based on the system used in the Auto-pneumatic mechanism) will serve the purpose of description.

It will be observed that we have a governing bellows, or auxiliary equalizer, held open by an expansion spring. This bellows stands in the channel from pneumatic action to bellows so that air displaced from the action must flow through it on the way to the bellows. A small hinged valve-block stands over the channel running to the bellows, and is pressed downwards by a spring on to the stop-block on the moving wall of the auxiliary equalizer or governor bellows. It is plain that unless (as shown in the illustration), the valve block were held up forcibly by the button on the threaded wire, it would drop down over its orifice in proportion as the governor might close under pumping. But as normally arranged, the wire is placed to hold the block up and away from the stop block of the governor, and so even if the governor does close, it does not cut off the air passage. If, however, the accent lever on the keyslip of the player is thrown over, the wire drops and allows the accent valve block to fall on the stop-block, thus

permitting the governor to act, for now the cut-off comes into action and the air passage is reduced in area so that the available vacuum is low enough to give only light power and soft playing. When, conversely, the accent lever is thrown back to its normal position, the wire again pushes up the valve block and the governor is again thrown out of action. It is evident that by alternating from low to high pressure, a series of instantaneous changes from soft to loud can be had, thus giving accentuation. This device is sometimes called the "soft expression governor," although the name is inadequate and misleading. "Expression governor" is correct.

Various other systems and types are used, but the above described method shows the principle thoroughly. It is simply a case of the governor being normally cut out of action, and then of having it thrown into action, to diminish loudness when required.

The same effects could be had by a pneumatically operated pouch valve, with a button instead of a lever. Like-wise, the accenting effect can be had by perforations in the roll operating on a pouch-valve as aforesaid.[1]

Sustaining Pedal Pneumatic. In many players the sustaining pedal is operated by a direct mechanical lever system without the use of any pneu-

[1] It is well to say again that my "Piano-Playing Mechanisms" contains a very complete detailed discussion of all these points.

matic device. But the practice is now universal of effecting also an automatic control of the sustaining pedal effects, through perforations in the music roll. At the same time many have expressed a preference for a pneumatically operated button instead of a direct lever. In this case a large pneumatic equipped with a valve system is placed near the bottom of the piano, adjacent to the damper lift-rod and connected with it so that the rod can be raised when the pneumatic collapses. This pneumatic system is connected to the main bellows system by means of a tube, and so, when the player is working, the vacuum chamber of the system is in a state of partial vacuum. Hence when air is admitted under the valve pouch or pouches by depressing a button or by opening a perforation in the tracker-bar, the pneumatic collapses and the sustaining pedal action operates, lifting the damper from the strings.

Soft Pedal Pneumatics. Another very common expression device is a pair of pneumatic systems connected with the bellows system and placed on each side thereof, or above the line of hammers at bass and treble ends of the piano, whereby the hammer line of the piano, artificially divided by a split auxiliary rail, may be raised towards the strings of the piano, all together, or one half at a time. The method of operation is just the same as described for the sustaining pedal action, except

that the pneumatics can be made smaller, since the weight to be overcome by each is not great. A pair of buttons on the key-slip controls the admission of air under the valve systems of the pneumatics. When half the rail is lifted, while the other half remains in normal position, the blow of the hammers which rest against the former, is shortened, with resultant softening of the sound produced by them. Thus, in a somewhat rough way, the accompaniment part of a composition may be subdued as against the melody voices.

Sometimes a pair of direct acting finger-levers on the key-slip is used to lift the split hammer-rail without resort to pneumatic devices.

What is known as the "floating" hammer-rail is also sometimes used. This is simply an arrangement whereby the hammer-rail and the ordinary piano soft pedal action are attached to the moving wall of the equalizer of the bellows system so that as the equalizer sways back and forth the hammer-rail is moved forward towards or back from, the strings. On hard pumping, when the equalizer closes up, the hammers recede from the strings; and on soft pumping, when the equalizer opens again, they approach the strings, thus modifying the length of the hammer blow in accordance with the pumping, and imparting a more flexible quality to the dynamic control of the player.

Action Cut-Off. In all player-pianos the action

is cut off from playing whilst the motor is rewinding the paper, by a door thrown across the main passage from action to bellows. When an expression governor is used, this cut-off is usually incorporated in the same box with the rest of the governor, and when two are used two such cut-offs are necessary, one for the bass and the other for the treble side of the pneumatically divided action. This door is usually operated by the direct mechanical action of the re-roll lever, which at the same time shifts the gear on the motor and opens the re-roll valve in the tempo-box. Sometimes, however, a pneumatic cut-off is used (Gulbransen, Cable, etc.) which operates by the re-roll lever opening an air passage which lets air down into a partial-vacuum chamber, raising a pouch and thus cutting off the piano action by covering the windway.

Re-Roll. The re-roll operates in the same way, through a re-roll lever, whereby the gear of the motor transmission is reversed and simultaneously a large valve is opened in the tempo-box not passing through the governor, whereby the motor can be speeded up in re-rolling. Sometimes a pneumatic gear-shifting device is used.

Silencer. When a pneumatic action-cut-off is used, another button may also be placed on the key-slip letting in air to operate the cut-off valve without changing the transmission gear of the

motor. Then the motor will run forward without the action playing, as is sometimes required for passing rapidly over a part of a roll which the performer does not wish to play. As sometimes built, the "silencer" also opens a large re-roll valve in the tempo-box, again without shifting gears, so that the motor can race ahead. This is only possible, of course, when the re-roll valve is controlled by a pouch instead of a direct-action slide-valve.

Bleed-Holes. All the valve systems described above as operating the various non-speaking pneumatics, require, of course, the usual "bleed-holes" or "vents" for the purpose of flushing out the air-tubes running from tracker bar or button.

Top-Action. The top-action, so-called, of the player piano consists of (1) the pneumatic stack, (2) the motor, and (3) the tracker-bar with its incidental accessory devices. Let us take these in order.

Pneumatic Stack. In the previous chapter I described the principles of design in a pneumatic action controlled by a single valve. This description, roughly speaking, holds good for all players of what is called the "single-valve" type, which means the type where one valve only is used between the tracker-bar and the speaking pneumatic. The so-called "double-valve" type is exactly the same, save that between the valve which directly

controls the pneumatic, and the tracker-bar, is another similar valve called the "primary" valve. This valve is lifted by the air which flows down the tracker tube and in lifting exposes an opening of larger size than the tracker perforation, down which flows air to the "secondary" valve, which directly controls the pneumatic. The two valves therefore are interdependent, neither one being effective unless the other is also effective. It is not true, as may be seen by examining any double valve action, that the one valve operates the pneumatic if the other does not. The main reason for the use of the second valve is found in the desire to use a pneumatic larger than can be effectively exhausted by the operation of a valve small enough to be readily controlled by the amount of air which can flow down the tracker tube in any given time.

Only one vent or bleed-hole is needed in the "double" action, as the secondary channels are flushed by their air flowing back into the primary chamber and thence out to the bellows.

Assembly. The pneumatic stack is assembled above the keys, with the pneumatics, in some sort of operative relation to the piano action, whether directly by contact with the wippens of the action or indirectly through fingers or rocking levers. Whether the pneumatics face forwards towards the front of the piano keyboard or towards the strings, makes no special difference. The valve

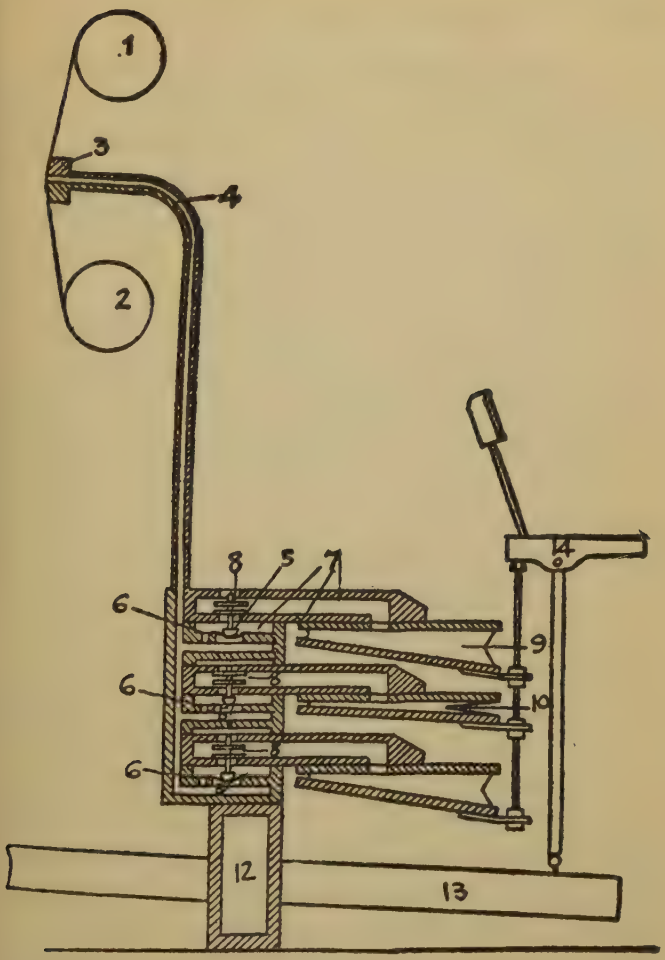


FIGURE 26

Sectional view of Single-Valve Action showing pneumatics open and closed.

1. Music roll.
2. Take-up spool.
3. Tracker-bar.
4. Duct.
5. Pouch.
6. Vent.
7. Reduced pressure chamber and passage.
8. Valve disk.
9. Pneumatic open.
10. Pneumatic closed.
12. Main passage to bellows.
13. Key.
14. Piano action.

system of the single valve stack is mounted so that each pneumatic is placed immediately above or below its valve, in two, three, or more banks. The secondary valves of the double system are placed in a chamber behind the pneumatics with the primary chamber and its valves above. It is usual to assemble the stack so that pneumatics can be detached from their positions and the valves taken out, cleaned and regulated. In some players a separate channel above the action is provided to carry the vents, and this channel then exhausts into the pneumatic stack, or directly into the bellows system.

Motor and Transmission. No special further description of the motor and transmission, in addition to what already has been said in the previous chapter is needed here. In fact, it only remains to recount that four, five and six single-unit bellows are variously used by makers, some with a valve slide to each pair and some with a slide to each individual; whilst again motors are made with double units, having two bellows, one above the other, working on each connecting rod. Some special types are also known, such as the early cylinder motor of Gulbransen and his later models with their oscillating and rotary valves. But in all cases the principle involved is that which has already been described.

The spring-actuated "Apollo" motor must also

be remembered, but it needs no special description here.

The transmission is a simple form of gear set, whereby the motor may drive either the take-up spool, for winding forward, or the chucks on which the roll turns, for re-winding at the close of a piece.

Spool Box. The spool box is a rectangular open frame in which are placed the tracker-bar, take-up spool and the music roll chucks, in addition to any tracker-bar or roll shifting device that may be incorporated. Its various parts may be described as follows:

Tracker-Bar. The tracker-bar is usually of solid brass pierced with 88 perforations, nine to the transverse inch, and with any extra perforations that may be required for the non-speaking pneumatic devices. From its rear the perforations branch out into tubes of rubber or metal which carry from each to its corresponding valve and pneumatic in the pneumatic stack. Sometimes the tracker-bar can be shifted by a thumb nut in the spool box, so that any failure of perforations in the paper roll to register properly with the tracker-perforations, can be corrected. In other cases, take up spool and music roll chucks are moved by a mechanical device.

Extra Perforations. Extra perforations are used as follows: A large perforation at the left

side for the sustaining pedal, small perforations in duplicate at either side for automatic accent devices[1] and marginal small perforations for automatic tracking devices (see *infra*). In some cases the latter perforations are superseded by movable tongues of metal or similar devices to press against the edge of the paper. Player-pianos of the electro-motor-driven type have also additional perforations to operate automatic start-and-stop pneumatics placed on the bellows system and working into the tempo and re-roll box.

Automatic Tracking Devices. Although there are a dozen different varieties of these, the intention in each case is the same and the principle similar. The idea is that if the paper shifts transversely in the course of its longitudinal travel, its own shifting shall operate devices to bring it back into line. What is probably the best known of all these devices works as follows: At either margin of the tracker is a pair of very small holes leading to tracker-tubes which run into a valve-system controlling pneumatics, one to the outer and one to the inner, pair of holes. These pneumatics are connected with a lever system to the left hand music-roll chuck, so that this chuck is moved transversely from left to right, accordingly as the corresponding pneumatic is operated. The music roll is always normally held hard against this movable

[1] The automatic expression devices are completely treated in "Piano-Playing Mechanisms."

chuck by the pressure of the spring in the other (left-hand) chuck. When the roll travels as it should, in true register, its edges just cover each pair of marginal perforations. When, however, the paper shifts transversely, through any cause whatsoever, and so is thrown out of register with the tracker-bar, one pair of holes is covered, which lets air down the corresponding tracker-tubes, operates valves and the corresponding pneumatic, and causes the movable chuck to be moved transversely so as to push the paper back into register again. The box on which the valves and pneumatics are mounted is placed at the left side of the spool box, the side opposite to that on which the motor stands.

There are a dozen types of this device, as I have said, but examination of them will show that they all operate in essentially the same way.[1]

The "Reproducing" Piano. During the last few years a type of player-piano known as the "reproducing" piano has been produced to reproduce the recorded playing of pianists. Each of these instruments consists essentially of a player-piano to which has been added devices for controlling the expression pneumatic through marginal perforations in the music rolls. The bellows system is motor driven and includes pneuma-

[1] The well known tracking device of Brand works entirely by friction and uses no pneumatics at all.

tic devices to permit the starting of motor, stoppage of motor and cut-off of pneumatic stack when required at the beginning and the end of a piece respectively. These are controlled by additional perforations in paper and tracker-bar. The principle of operation and the various current systems (Ampico, Duo-Art, Welte) are fully described by me in another book.[1]

65-Note Players. The 65-note player is a thing of the past, but, of course, many were made and a few are yet in use. They cannot be said to differ very much from the more perfected types of which they are the ancestors, save that the parts are larger and clumsier and on the whole much less accessible. In many cases the pneumatic stack is built below the key-bed so that it is necessary to withdraw the latter before one can get at the action at all. Although only 65 notes are operated, so that there are 23 fewer pneumatics than we need today, old pianos of this type are often quite astonishingly clumsy and huge. It is well to note the following features of the 65-note player, exhibiting differences from modern player-pianos:

1. The tracker scale is wider, having six perforations to the transverse inch. The roll is, therefore, somewhat wider also.

2. The rolls are pinned at the flanges, which

[1] "Piano-Playing Mechanisms," N. Y., 1925, Edward Lyman Bill Inc.

means that a different sort of chuck to hold them is needed.

3. The action is sometimes placed below the keybed and when this is so it is nearly always necessary to take out the entire bed to get at the action for repair or regulation.

4. Combined 65- and 88-note tracker-bars were used for a time after the first appearance of the 88-note player. In all of these it is well to look out for leaks in the tracker and for all the annoyances thereby caused. These combination players are now no longer made, however, except on order.

The Cabinet Player. Although the old cabinet or outside player is now obsolete, a great many of them were made, some with reed organs built into them and others embodying all manner of freak experiments. The range was either 58 or 65 notes and special rolls were therefore often necessary. The following hints may be found useful as a condensed guide to the construction of these old instruments:

Bellows. It will be found, usually, that the bellows of the oldest cabinet players were developed much on the order of the reed organ, particularly in respect of having a large equalizing unit and large exhausters. These bellows are essentially slow moving and do not lend themselves to quick changes of tension level. They are covered with the kind of rubber cloth used for the reed organ, and fastened at the bottom of the cabinet in such

a way that to get at them it is necessary to take out the entire mechanism from the cabinet. In fact, it will be found that usually it is not possible to get at any parts save the motor and tracker-bar without taking the whole thing from its case; in itself often a difficult and irritating job.

The various parts which go to make up the bellows system, such as governors, gate-boxes and action-cut-off valves, are usually found buried inside the bellows on the older cabinet players, and can only be reached through them.

Pneumatic Action. The valve system of the cabinet player is either of the simple single valve type described in essence in the last chapter, or of the primary-secondary type as described in the present chapter. There is nothing special to be said about the make-up of such systems in the special case of the cabinet player, save that the valve boards are sometimes found glued together in such a way as to prevent any access to the pouches.

Motor. The motor is of the usual type, but often has only three units, which sometimes are placed at the bottom of the case. The spring-driven motor is used in the Apollo, Simplex and Needham cabinet players.

Expression. The expression control of the cabinet player varies according to make, but the most popular arrangement is as follows: One tempo lever, one re-wind lever, one sustaining pedal lever

giving direct pressure on the pedal foot of the piano, and one lever working an expression governor to switch the playing power from high to low tension at will.

In later models of cabinet players, automatic accentuation devices were introduced equivalent to those which have been adopted in similar players of the interior contained type. Such modern cabinet players, however, may be considered as virtually equivalent to the present interior mechanisms, as they contain the same devices and are built the same way.

These brief remarks will suffice for description of a type which has almost entirely passed away and no longer need engage our serious attention.

Chapter XIII

REPAIR OF PLAYER MECHANISM

Within the meaning of the word "repair," as used in this chapter, I understand to be included all matters pertaining to the regulation and maintenance of players in good order during their effective life, as well as such direct reparations as may be necessary through the breakage or destruction of parts. I do not propose to attempt an exhaustive listing of all the possible troubles that may occur, but shall give here some gleanings from my own experience and from much observation of others' work, with the intention of providing a general guide which shall enable the learner to find his own way through the most difficult problems.

In the first place it ought to be realized that the number of possible troubles that can occur to a player-piano is limited. All may be traced to a few broad causes, and when these are known and understood, any other problem that may arise can be reasoned out. I shall begin by discussing the possible troubles occurring to players that remain structurally and organically perfect, and shall then say a little about the work of repairing dam-

aged and broken parts on older machines. In short, the first part of this chapter shall treat of maintenance, the second of actual replacements.

Seepage. The fundamental cause of more than half the ills which affect player-pianos is seepage. It is of course obvious that in a machine like the pneumatic player action, operation whereof depends upon the constant maintenance of a reduced pressure within the mechanism, any leakage of air inwards from the outside must be prevented at all costs. Yet it is also plain that this seepage inwards is inevitable to some extent, for the simple reason that the outside air presses upon the outer walls of the mechanism everywhere with a definite pressure directly proportional to the reduction of pressure within. The higher the vacuum within, the greater the pressure without. Hence it can easily be seen that there is everywhere a constant tendency towards the seepage of air inwards in all places where such seepage is conceivably possible. Thus, for instance, we know that when the button of the primary valve is thrown up, atmospheric air flows in beneath the button and into the secondary channel. Now, right operation of the mechanism depends upon the primary buttons seating upon their seats so cleanly that there shall be no seepage of air under them until they are deliberately raised by the operation of the paper roll. Any leakage under any of these buttons

means that the corresponding secondary valves are operated, and then we have what is known as "ciphering"; which means, pneumatics speaking when no perforations in the roll call for them to speak. That is one illustration of the seepage problem.

It is equally plain that through seepage the pneumatic sustaining pedal devices operate when the control button is at rest. Seepage is responsible for the re-roll speed of a motor being maintained when driving forward. Seepage is responsible (when a re-roll is pneumatically handled), for the mechanism playing when re-rolling. Seepage beneath the pouches of a tracking device may be responsible for constant bad tracking of rolls. And there are many other possibilities in the case.

Precautions Against Seepage. It is, therefore, clear that the maintenance of air-tight conditions is the prime duty of the repairman. To this end the following general hints will be found useful:

1. Always see that the screws in valve-boards and other important places, such as governor boxes, etc., are well tightened.

2. Do not drive screws roughly and forcibly, but always turn them in as far as possible with the fingers, and then finish with screw-driver. Do not force too tight. Overdrawn screws are a most prolific cause of seepage.

3. When it is necessary to take off a cover from

a box or bellows, or valve-chest, be extremely careful to see that the replacement is made exactly as was the detachment. In other words, mark the top and bottom of the box when detaching it and see that it goes back the same way.

4. When detaching a valve seat, see that it is marked so as to facilitate replacing in exactly the same position; and if it was shellaced or glued in place, re-shellac or re-glue it.

5. See that the valves work easily and are not prevented from seating by grit or dirt lodging on the seats. Sticking or blocked secondary valves sometimes prevent entirely the formation of a vacuum in the chest, being wedged in a half-way position and allowing air to be drawn constantly from the outside into the chest through their outer seats.

6. See that all hose connections are tightly on their nipples and if such connections have tightening bands, see that the latter are tightened accordingly.

Motor Troubles. The pneumatic motor of the player mechanism is timed to run as follows:

2 feet per minute of paper to pass when indicator shows 20
3 feet per minute of paper to pass when indicator shows 30
4 feet per minute of paper to pass when indicator shows 40
5 feet per minute of paper to pass when indicator shows 50
6 feet per minute of paper to pass when indicator shows 60
7 feet per minute of paper to pass when indicator shows 70

and so on upwards to the 130 mark on the tempo dial, where the indication is for 13 feet of paper

per minute to travel. These speeds are commonly tested on a test roll which is marked out in feet and half feet, so that the time can be taken by the watch.

Test-Roll. A test-roll which allows for the separate sounding and repetition of each of the 88 pneumatics, as well as for timing motor speed, is an essential element in the kit of the player repairman.

Motor Slow. If the motor runs at speed slower than indicated above, the spring of the motor governor must be strengthened as explained in previous chapters.

Motor Fast. If the motor runs too fast, spring must be weakened.

Motor Drags. If the motor drags on light pumping (does not run fast enough, loses speed), the governor closes too much. If the speed has been regulated through the governor spring for normal pumping, the screw which is placed to limit the closing of the governor or its cut-off must be adjusted to open the governor farther.

Motor Races. If the motor races on hard pumping, the governor does not close enough. If speed is right on normal pumping, then adjust screw so as to make governor close a little more on hard pumping.

Motor Hitches. If the motor runs irregularly and in a sort of gasping way, perhaps losing power

rapidly or failing under hard work, as towards the end of a heavy roll, this probably means seepage under the slide-valves or incorrect adjustment of them. In the first place, see if the slides sit flat on their seats. If they do not, take them down and have them trued up. Wooden slides can be sandpapered flat. The seats also should be sandpapered and then burnished with powdered graphite (not grease, tallow or other fatty substances, but pure graphite only). In the second place, if the motor runs unevenly, disconnect slides and then carefully place each one in its true extreme position over the ports in both extreme positions alternately, marking the seat accordingly. Then adjust the connecting rods so that slides reach these positions correctly.

Motor Races All the Time. In this case the re-roll valve in the tempo box is probably being kept open. Adjust it accordingly. But if a silencing valve is used, look to this and see whether there is anything holding it open on the motor side; as for instance a leak, allowing air constantly to flow under the operating pouch and lift the valve.

Action Plays When Re-Rolling. In this case it is evident that the action-cut-off valve does not close when the re-roll lever or button is operated. In cases where a pneumatic device is used it is possible the leakage under the pouch or between the operating button and its seat may be responsi-

ble. Otherwise, a broken connecting rod is the most obvious thing to seek.

Action Does Not Play. Action-cut-off valve remains closed. Examine the manner of operation and apply remedies as suggested above.

No Vacuum in Action. See if secondary valves are held off their seats by dirt or verdigris gathering on seats, or by sticking of guide pins; provided, of course, that the bellows system is working all right.

Pouches Too Stiff. Sometimes pouches are made stiff by age or warping of pouch board, so that they hold valve stems off their seats and prevent vacuum chest from becoming duly exhausted. This defect is sometimes observed by player failing to gain vacuum when pumped. Take off valve board and rub down pouches with fingers. If this will not do, regulate valves to give more play between buttons and pouches.

Player "Lacks Power." Usually this defect is manifested in a certain lack of "resistance" under the feet and is often to be remedied simply by increasing the stiffness of the equalizer springs. If there are two equalizers it is often well to stiffen only the one which is more heavily spring-expanded. Sometimes an extra wooden spring outside the equalizer is the indicated remedy.

Repetition Bad. Probably the vents or "bleed-holes" are clogged and in this case need simply

to be cleaned, when the trouble will disappear. Adjustable bleed-holes, as in some players, may have been maladjusted by some previous repairer. Lost motion between pneumatics and piano action is also to be considered as a possible contributor to this defect.

Repetition Good but Power Weak. Bleed-holes are probably too large and should be adjusted accordingly, if player has adjustments for this purpose. But this defect is very unlikely to be observed in players with fixed bleed-holes.

Player Plays Hesitatingly. See if primary valve stems stick in their sockets or are too tight in them. This will cause primaries to move slowly and delay action of player. Similarly, see if secondary valves move slowly through stickiness of pins or other similar causes.

Travel of Valves. In almost all cases it may be safely set down that primary valves need not and should not rise more than 1/64″. Secondary valves need about 1/8″ travel in most cases.

Pneumatic Ciphers. See above on seepage. Ciphering is due to the valves operating independently of the paper, so that a pneumatic collapses as soon as pumping starts. Look for leaks in the tracker-tube, or dirt on valve seats, or leaks from channel to channel in valve boards or connections.

Pneumatic Silent. If a speaking pneumatic does

not collapse when it should, listen for a hissing sound, which indicates a torn pneumatic. Otherwise see if tracker-tube or channels are clogged or valves shut by dirt.

Dampers Always Off. Sometimes (see above, "seepage") air gets under the sustaining device control button and keeps sustaining pedal pneumatic partly collapsed. Other similar defects may cause this pneumatic to remain collapsed.

Dampers Do Not Rise on Low Vacuum. All pneumatic sustaining devices have the defect of requiring considerable power to work them. If they work well on lower power, then this means that bleed-hole and rise of valve are cut down so much that, although the pedaling is not affected, the operation of the pneumatic is slow. Vice versa, if the pneumatic closes sharply, it makes a lot of noise and takes up much power. A happy medium is the only aim possible.

Soft Expression. The expression governor can be regulated to determine what degree of power shall be available when the soft expression is in action. The stiffer the spring is made, the louder will the player play on soft expression and vice versa.

In players which have divided soft expression, one half of the vacuum chest is affected by each governor. The action-cut-off valve is then also divided; one half being required in each expres-

sion box. This should be remembered in dealing with such players.

Regulation in General. Of course, it would be easy to go on indefinitely setting forth directions for remedying possible troubles, but the foregoing covers the really essential points and the student should be able by careful study of the previous chapter to reason out for himself any further problems of the same sort. It is mainly to be remembered that the player mechanism is to be considered well regulated when it plays well. If its playing is satisfactory to the user and to the tuner who cares for it, there is really no more to be said. Certain things are requisite to the proper working of the player mechanism and these have been set forth above.

Patches and Replacements. The actual replacement of parts which have become worn out is not often necessary, but in old cabinet players and even in older 65-note player-pianos still in use, one sometimes finds it necessary to re-clothe bellows units, re-pouch valves and so on.

Stopping Leaks in Boards. When cracks appear in valve boards it is best to fill them in with shellac. In fact, any places where any possibility exists of leaking joints or porous wood, may always advantageously be treated in this way. If cracks are really wide, it may be better to fill in with soft wood glued in place, and then cover with a thin

patch of pneumatic cloth on both sides, afterwards shellacking over the patch.

Cracked Pneumatics. The cloth sides of pneumatics, especially those of the motor, wear out in time at the hinges. In this case, it is necessary either to cement a small patch over the cracked place or—if the crack is wide—perhaps to reclothe the pneumatic. Especially is this often necessary on old motors. The procedure in this case is as follows: Carefully cut off the old cloth very close to the edges of the wooden walls, so that when cut off the entire cloth can be laid out on a table in one piece forming a pattern for the new cloth. The narrow edge of the cloth where it was glued on to the walls cannot always be removed readily, but in that case simply cut out as closely to the edges as possible. Then lay the old piece down on a new piece of cloth, allowing enough extra width to take care of the thin edge which is to be glued on the boards or wall of the pneumatic. Take a file and smooth off the edges of the pneumatic boards or walls, so as to get off all the old cloth that will come off. Then get good hot glue, spread it over the edges of one board and apply the cloth, smoothing it well down with the hand and ironing it finally with a small iron fairly hot. Then do the same on the other wall of the pneumatic, allowing a little time for the first to dry. Be careful to see that the dimensions are preserved,

especially as to width of opening when the cloth is glued on. For speaking pneumatics, a mercerized rubber-coated cotton is often used, gauging .0045″ to .0075″. For motors the same firm manufactures a rubber cloth, either double or single texture, gauging .008″ to .015″.

Bellows Repair. The corners of the exhaust units sometimes show signs of wear but the toughness of the cloths used and the comparatively slow movement of the units in operation permit effectual patching without any necessity for entire recovering. Patches should be of the same material as the original cloth and should be glued on with hot glue if the cloth is a jean or a twill; and with rubber cement if the old-fashioned rubber bellows cloth is the material.

Bellows flap-valves sometimes become leaky through porosity of the cloth. They can be covered with a strip of bellows twill, or simply replaced.

Double texture jeans and heavy twills are used for covering bellows today. The old rubber cloth is obsolete.

Pouches. To replace broken or cracked pouches, take off the old leather as carefully as possible and cut a new piece of the same size. Scrape glue-surface clean, put on hot glue and press down with a wooden block cut to fit the orifice. Kid is often used for pouch leather on modern players, but on

old ones sheepskin was sometimes used. The use of this latter should be avoided as it tends to crumble. In my opinion, a rubber-coated silk cloth is the best, and such cloths should gauge from .003 to .004 inch.

Squeaky Springs. Treat coiled springs with vaseline. If fan springs squeak see where the rust is in them and clean it out.

Squeaky Slides. Squeaky slide-valves in tempo boxes and elsewhere should be treated by smoothing off their seats and contact surfaces and rubbing on graphite powdered, or from a soft, heavy lead pencil. Never use grease in any form.

Overdrawn Screws. Screws should always be counter-sunk and provided with metal washers when used to secure valve boards and other places where air-tightness is desired. Do not turn overdrawn screws, but withdraw, plug their holes and re-insert them. Overdrawn screws always mean air seepage.

Leaky Tubes. Old rubber tubing is sometimes found crumbled and leaky. Do not bother about it, but simply replace it with new lengths. Old hose connections often leak also and it is better to replace them. Metal hose pipe connections should be well screwed down and, if necessary, seated on a coat of shellac.

Metal tubing does not often crack or otherwise suffer leakage troubles, but occasionally a jar or

shock will crack such a tube at a joint. The best remedy is to cut out the affected part and join up with a piece of rubber tube; or else use the soldering iron.

Old Player-Pianos. Player-pianos made in the 65-note days were usually built with a child-like confidence in their infallibility; or so at least one should imagine. Their builders seem not to have considered that there would ever be any special need to take them apart, and, in fact, may perhaps have thought that they would be better untouched; for certainly to disentangle them from the piano is always a formidable and often a hopeless task. The repairman may observe that many of these old pianos are built with the entire pneumatic stack, in addition to the bellows-system, under the key-bed, while the spool box remains above. Naturally, it is not easy to get such a mechanism out of the piano and in many cases it is necessary to take out the key-bed, which in fact is usually arranged accordingly. In one case (old Cecilian 65-note) the key-bed carrying the pneumatic action, the keys, the piano action and the spool box, can be separated from the back of the piano.

Leakage, slowness of motor, hard pumping and general debility are to be expected in these player-pianos, for they were built at a time when the whole industry was in an experimental state and when the general level of scientific knowledge in

the factories, never high, was even lower than it is now. Hence, as can easily be understood, all kinds of impossible constructions were made the subject of experiment. The repairman is oft-times called on to use his skill on specimens of this sort.

In any case it may be said that the principles already briefly laid down in this book (and more completely in my "Piano-Playing Mechanisms"), apply to the old as well as to the new, nor has there been any radical alteration in essential methods. Principles, of course, are exactly the same today as they were twenty years ago; refinement in detail has been accomplished, but scarcely anything more.

Cabinet Players' Individualities and Peculiarities. Similar observations apply to the older cabinet players, with certain additions. The older cabinet Angelus and Apollo were made with a 58-note range. The Angelus music rolled the reverse way. Apollo rolls were made without pins, whereas all other contemporary 58- and 65-note rolls had pinned flanges. Cecilian music was made with a long tracker-bar provided with extra size perforations at the bass end. Such players had to have two tracker-bars. Some Apollo players were built in a form known as "Apollo Grand," having an octave coupler to throw in an extra octave of pneumatics at the bass and treble extremities.

In general it should be remembered that the cabinet players, even more than the old 65-note player-pianos, were experimental. They, therefore, are found in vast variety of constructional detail, but it may always be safely assumed that their peculiarities are due rather to imperfect grasp of fundamentals on the part of their makers than to any excellences now unavailable or unused.

These brief hints and suggestions are given with the idea of suggesting methods rather than attempting to convey a definite answer to each possible definite problem. The latter task would be endless.

In conclusion let me give a short list of materials and tools that the player repairer should always carry with him.

Test roll.
Vacuum pump for tracker-bar.
Rubber tubing for tracker-tubes.
Hose (two sizes) for main connections.
Shellac in liquid form with bottle and brush.
Glue.
Rubber cement.
Kid (leather) for pouches.
Rubber covered silk cloth for pouches.
Rubber coated cotton cloth for pneumatics.
Rubber cloth for pneumatic of motors.
Special bellows cloth for bellows repairs.

Rawhide washers and strips for bearings of pedals, bellows, connections, etc.

Miscellaneous threaded wires and buttons.

Leather buttons.

Miscellaneous valve buttons and stems, valve seats, etc.

Other materials and tools will suggest themselves to the repairman as his needs and his experience alike grow.

A Last Word. It is not true that a good workman never quarrels with his tools; though perhaps a bad workman always does. A good workman never quarrels with good tools; but always quarrels with bad ones.

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THE END.

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